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THESIS

HEAT TRANSFER STUDIES AND FLOW VISUALIZATION OF A RECTANGULAR CHANNEL WITH AN OFFSET-PLATE-FIN ARRAY

by

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March 1996

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HEAT TRANSFER STUDIES AND FLOW VISUALIZATION OF A RECTANGULAR CHANNEL WITH AN OFFSET-PLATE-FIN ARRAY

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ABSTRACT

The heat transfer characteristics and flow visualization of a 10X scale version of internal offset-fin plate array within the liquid flow-through module for electronics cooling were investigated experimentally using water as a cooling fluid. By varying power input settings and coolant flow rates, the heat transfer effect from the plate array to the coolant water was investigated. Additionally thermochromic liquid crystals were spray-painted onto the plate to determine the temperature distribution within the heat transfer surface, as compared to the readings from the attached thermocouples. Finally a flow visualization using the dye-injection technique was to study the flow patterns of the coolant through the fin array.

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FORWARD

I wish to thank the following people for their continued assistance in helping me complete this thesis. First of all to my family who suffered through its completion, especially to my wife for her love and dedication. Second to LT. Bill Plott, LT. Don Avenger and LT Phil Pall who helped me through NPS. Finally to Dr Kelleher and CDR Gray, who saw me through the ordeal.

I. INTRODUCTION

A. ELECTRONIC COOLING

Electronic components have continued a rapid pace of increasing capability and decreasing size. With each increase in capability, there is a corresponding dramatic increase in the power density of the electronic chip. Therefore, designers are faced with the need to develop more efficient heat exchangers to cool electronic packages. Furthermore for avionic and shipboard applications, weight savings is also a key criterion.

1. Cooling Requirements

Electronic designers are restricted by two major constraints. First, for reliable operation of an electronic chip, the chip junction temperature typically must remain below 85 °C. This is a material limitation to ensure efficient transfer of binary data along the chip's electronic circuits [Ref 1]. Second, advances in micro-miniaturization continue to increase the power densities of electronic chips. Integrated circuit chips have heat dissipation requirements of up to 40 W/cm^2. Researchers are focusing on cooling the next generation of very-large scale integrated chips with a heat dissipation of 200 W/cm^2 [Ref 2]. There have been several approaches to enhance removing the heat generated by electronic components. These include heat sinks, forced convection air cooling, conduction cooling, and direct liquid immersion cooling. This study investigates the heat transfer effects of forced convection cooling a plate-fin-array which is conducting heat away from a mounted circuit card.

The U.S. Navy is particularly concerned with the use of printed circuit board modules, to ease troubleshooting and repair of electronic systems. A particular concern in military applications is how to achieve increased cooling capacity while decreasing system weight. A standard military circuit module is the Format E, Standard Electronics Module, (SEM-E), MIL-STD-1389. Presently the SEM-E card is limited to a heat input of forty watts from a printed circuit board populated with chips, weighing under two pounds. A typical one-tier Integrated Rack loaded with SEM-E cards weighs approximately 70 pounds. By increasing the electronic cooling capacity, the military can take advantage of higher density chips, without the liability of increased overall weight. The Standard Hardware Acquisition and Reliability Program (SHARP) is evaluating an advanced electronic cooling system at the Crane Division of the Naval Surface Warfare Center. The desired end is to effectively cool a 42-pound enclosure with 30 modules dissipating an average of 200 watts per card. To accomplish this task, a commercially available liquid flow-through-module (FTM) is being tested. [Ref. 3]

Compact heat exchangers are often used in industry. By definition, these heat exchangers have a large surface-area-to-volume ratio. The use of extended surfaces into the flow of the coolant provides additional surface area for heat transfer to take place. Fins enhance the heat transfer from the module surface to the coolant. These heat exchangers, seen in Figure (1), fall into three categories: offset fin, louver fin and parallel louver fin. The offset fin exchanger, the most common type, is the focus of this study.

The liquid FTM internally combines two thermal design concepts. First, three internal passages within the FTM direct the flow of coolant. These internal flow passages have internal fins. As stated previously, the advantage of the offset fin array is the increased heat transfer gained from the periodic interruption of the thermal boundary layer. [Ref. 5] Designed as a compact heat exchanger, the fin structure increases the heat transfer surface area inside the volume of the FTM. Second, the fins also increase the convective coefficient by disrupting the growth of thermal boundary layers on the surface [Ref. 2].

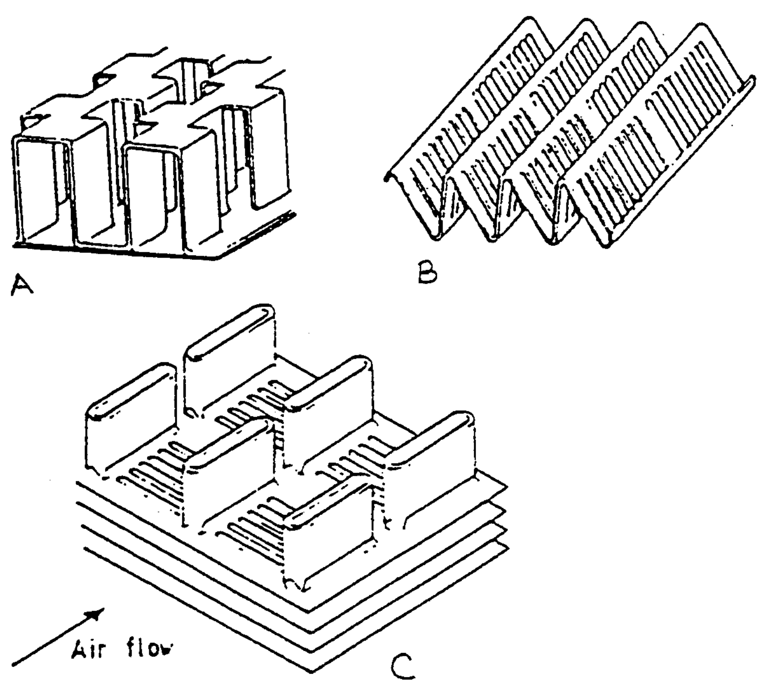


Figure 1. From Ref. 5, Enhancement geometries for compact heat exchangers, a) Offset-strip fin, b) Louver fin, c.) Louver fins on flat tube.

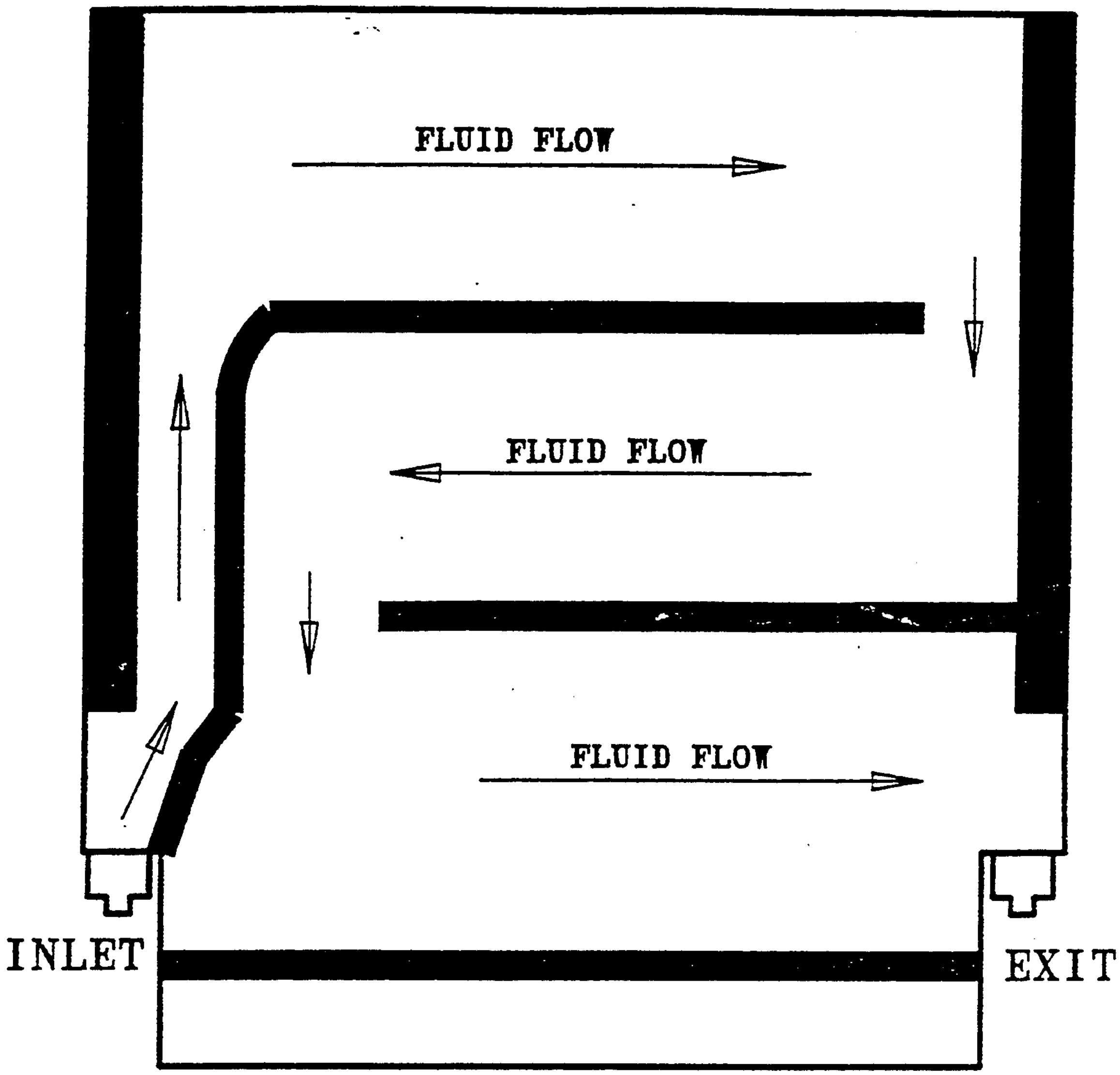
2. Offset Plate Finned Arrays

The fin array can be either internal or external. In this specific case, the fin array is internal in a flow-through-module (FTM) through which the coolant is pumped. Heat is conducted from the electronic circuit board from the circuit board to the module, sometimes using a heat sink. Figure (2) shows the internal flow path of coolant through the module. Each of the three internal passages contains an internal fin-array. These fins on the module's interior, as seen in Figure (3), enhance convective heat transfer to the coolant. The modular arrangement allows for a more self-contained coolant system, to avoid contamination and to ease the replacement of malfunctioning circuit board modules. [Ref. 4]

The offset fin plate heat exchanger is characterized by the geometry of its fins. An alternating interval pattern interrupts the fluid flow stream. It is important to note that the repeated interruption of the velocity and thermal boundary layers by each succeeding row of fins enhances heat transfer [Ref. 5]. Unfortunately the very geometry of enhanced heat transfer surfaces increases the number of dimensional variables. Modeling of the complex channel flow has been challenging investigators for several decades. Weiting developed the primary correlation for offset strip fin geometry in 1975. His empirical solution to describe heat transfer required a different constant for the Reynolds number exponent in the laminar and turbulent regions. This causes inaccuracies in predicting heat transfer in the transition region. [Ref. 5]

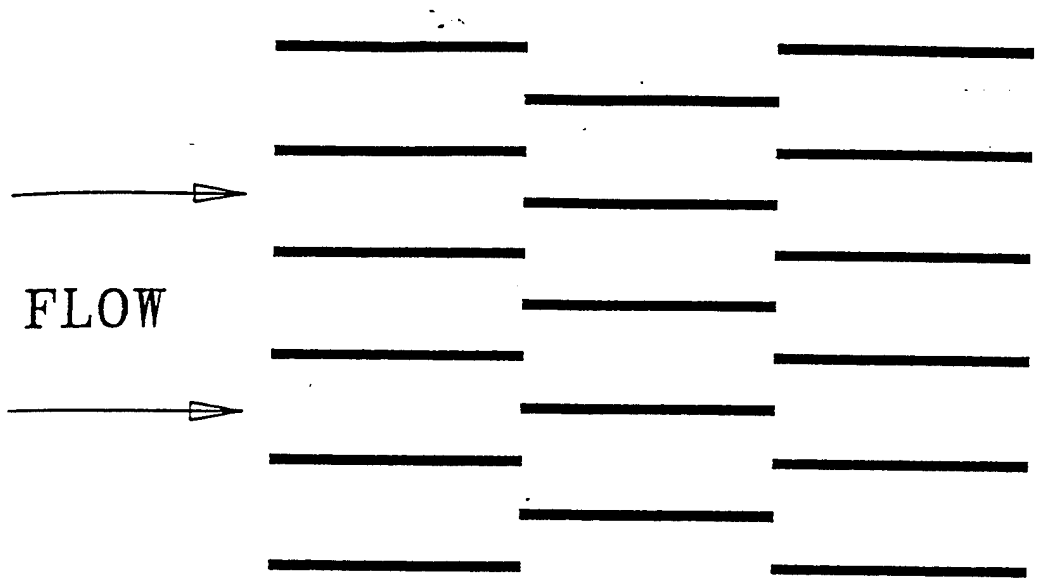
The geometry of the offset fin array has the following characteristic lengths: fin length (l), height (h), thickness (t) and spacing or pitch (s). Figure (4) shows the unit cell as defined by H. M. Joshi and R. Webb [Ref. 7]. The offset is the lateral displacement between the trailing edge of one fin to the next row's forward fin edge. Normally the next row's offset is half the fin spacing, or in the center of the previous row.

It was discovered that the ratio between fin spacing and fin length determines the amount of turbulence behind a fin [Refs 6-9]. The variation of the s/l ratio changes the frequency of the vortices within the wake flow. Unfortunately the friction and form drag of the fins causes increased turbulence that results in a pressure drop [Ref. 7]. Form drag can be reduced by using slender fins, to diminish the fin thickness's effect on momentum and heat transfer [Ref. 8]. If an optimum s/l ratio can be computed through a correlation, a subsequent optimization in required pumping power may result.



Module Thickness: 0.1 inch
Faceplate Thickness: 0.02 inch
Faceplate Material: 6061 Alum.

Figure 2. From Ref. 4, p. 2, the internal flow path of coolant through the FTM. Note the three separate internal passages which contain the fin arrays.



Lance Length: 0.125 inch
Fin Density: 20 Fins/inch
Fin Height: 0.06 inch
Fin Thickness: 0.006 inch
Fin Material: 3003 Alum. Alloy

Figure 3. From Ref 4, p. 3, Fin Pattern for test FTM. These are the original dimensions on which the model was based. The lance length is the fin length.

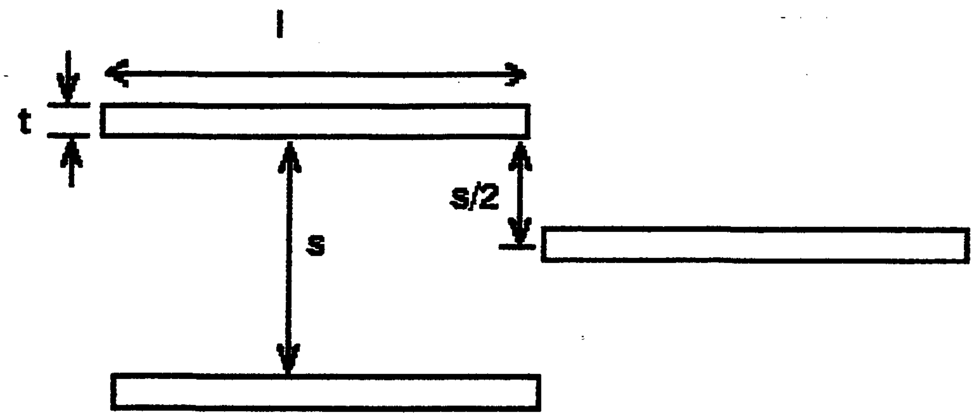


Figure 4. From Ref. 11, Unit cell dimensions of offset fin plate array. Height is in the normal direction.

B. PREVIOUS RESEARCH

Weiting's study focused on the heat transfer characteristics of air. Several studies have focused on refining predictive correlations for transitional flow [Ref. 8]. Results from flow visualization of plexiglass fins of various geometries within a water channel helped develop a criterion for transition to turbulence [Ref. 7]. The effect of fin pitch or spacing on the flow characteristics was extensively studied in Japan [Ref. 9]. Numerical solutions for two dimensional arrays for laminar flow and accounting for fin thickness, have been developed [Ref. 10].

It was Joshi and Webb who conducted the research which developed a numerical solution to the Nusselt (Nu) and the friction factor (f) for a laminar flow and a semi-empirical solution to the turbulent region. Through experimentation on a scaled up model, they formulated a method to predict transition to turbulence using a wake width based Reynolds number, Re_b. The wake width was defined as the fin thickness plus twice the momentum thickness at the trailing edge of the fin [Ref. 7]. Since the offset fin is common geometry for heat exchangers, an empirical solution could be optimized to determine the best fin dimension ratio for a desired heat transfer rate using various fluids.

Research into the optimal fin dimensions continued following the empirical correlations of Weiting. He had used an aspect ratio relating flow passage width and height. The plain longitudinal fin and the offset fin geometry were compared to learn the heat transfer rate of a fin in higher Prandtl number fluids. Fluids like Flourinert FC-77 ($Pr = 25$) were compared to water using correlations by Kays and Webb-Joshi. [Ref. 2]

Several authorities have reviewed the body of published research to create an accurate bibliography. Manglik and Bergles presented a compilation of current empirical data, correlations and qualitative observations up to 1987 [Ref. 8]. Webb updated this bibliography in 1994 through a review of various advances in modeling enhancement mechanisms to predict the effect of geometric variables and fluid properties [Ref 5].

Manglik and Bergles also presented the expected flow patterns observed in flow visualization experiments, reproduced in Figure (5). As also by Xi, et. al. they showed there are four distinct flow patterns. Pattern (a) in Figure (5) shows a smooth, laminar flow. Oscillations begin at the upstream edge of the second fin, then progress towards the trailing edge of the first fin as flow velocity increases, as seen in Pattern (b) and (c). Finally vortices develop off the trailing edge of the first fin at the highest flow rates as seen in Pattern (d). [Ref. 8]

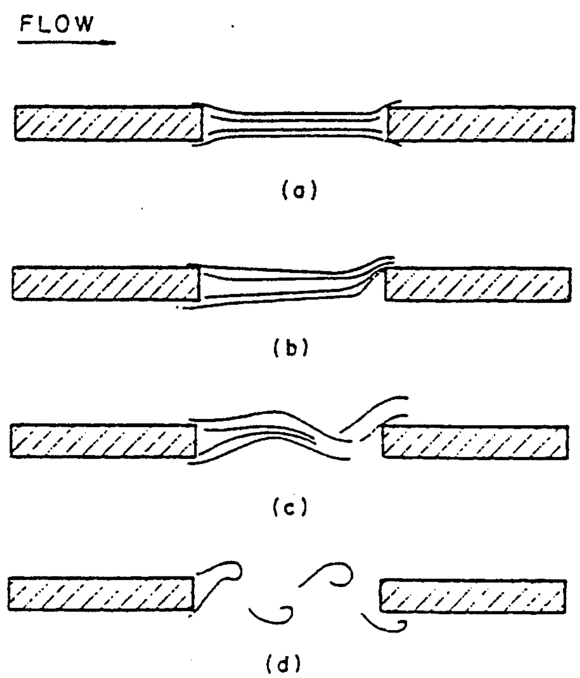


Figure 5. From Ref. 8, Flow Patterns observed in visualization experiments. Pattern (a) is a smooth, laminar flow. Oscillations increase as flow velocity increases in patterns (b) and (c). Pattern (d) has vortices off the trailing edge at the highest flow rate.

C. OBJECTIVES OF PRESENT STUDY

This study is a continuation of an experiment designed to investigate the heat removal capacity of a scaled-up version of the SEM-E sized flow-through module. Water as the cooling fluid was passed over a electrically heated plate with an offset-finned array. The surface of the array was coated with thermochromic liquid crystals to detect variations in the temperature distribution across the plate and fins. Flow visualization to confirm previous research was to be accomplished by dye injection. [Refs. 7-9] By varying the coolant flow rate through the fin passages and the power input, the effect of the Colburn j factor was also investigated.

II. EXPERIMENTAL APPARATUS

Since this is a continuation of a previous study, the experimental system was refurbished and adapted to fit the new requirements. The apparatus included a test section, data acquisition system, and a fluid circulation system. The author acknowledges the work of Lt. Jeffrey Masterson, who constructed the test section. This chapter borrows heavily from Masterson's thesis to provide a clear description and diagrams on of how the subsystems were constructed and used for this study [Ref 11, pp 9-15].

A. TEST SECTION

1. Base Plate and Fin Assembly

The base plate and fin assembly is a 10X scale model of the horizontal passages found within a liquid flow-through-module. Dividing the array into fin rows allowed the base and fins row to be milled from a solid piece, without the need to weld the fin onto the base plate. Seen in Figure (6), this was done by cutting 2.54 cm (1.0") thick aluminum 6061 alloy plate into 31.75 mm wide strips. These strips were then milled to the width of the plate. The fins were cut 15.24 mm deep into the aluminum strips using a specially made 11.76 mm diameter end mill. The base thickness was maintained at 10.16 mm. An offset of 6.64 mm was cut into one end. When this offset was alternated, it created the offset pattern of succeeding fin rows. Finally on each end, an additional 12.7 mm offset of base plate thickness was milled to serve as the lip for the plexiglass cover. [Ref 11]

The inlet and outlet plenum was milled from two pieces of a 10.7 mm (.5") aluminum 6061 alloy plate. These were milled down to the base plate thickness of 10.16 mm.[Ref 11]

Holes were then drilled in the plate's lengthwise direction through each fin row and plenum piece. Two threaded rods hold the plate assembly together. Rubber gasket was placed between the first row and the inlet plenum sections, and between the last row and outlet plenum sections. This was to reduce longitudinal conduction losses from the finned section into the plenums. Final assembly included the use of a bead of silicone rubber coating between each fin section to prevent leakage. [Ref. 11]

Prior usage left some hard water deposits on the plate. The plate was cleaned using glass beads under a sandblaster hood. The plate surface was then prepared for coating with thermochromic liquid crystals. This was a two step process. First, a commercially prepared, water-resistant, black base paint formulated for thermochromic crystals was spray-painted onto the surface with two thin coats. Then two coats of water resistant thermochromic liquid crystals was spray-painted onto the plate. Special care was taken to coat the fin faces without causing drips or pools.

Thermochromic liquid crystals react to temperature changes by changing color. The crystals are colorless until the red start temperature is reached. Then the color will respond over a set bandwidth by passing through the visible spectrum from red to blue with increasing temperature. [Ref. 12] The crystals chosen for this study had a red start temperature of 30 $^{\circ}$C and a fifteen-degree bandwidth. Response was tested by electrically heating the plate in air to observe uniformity of color over the entire plate.

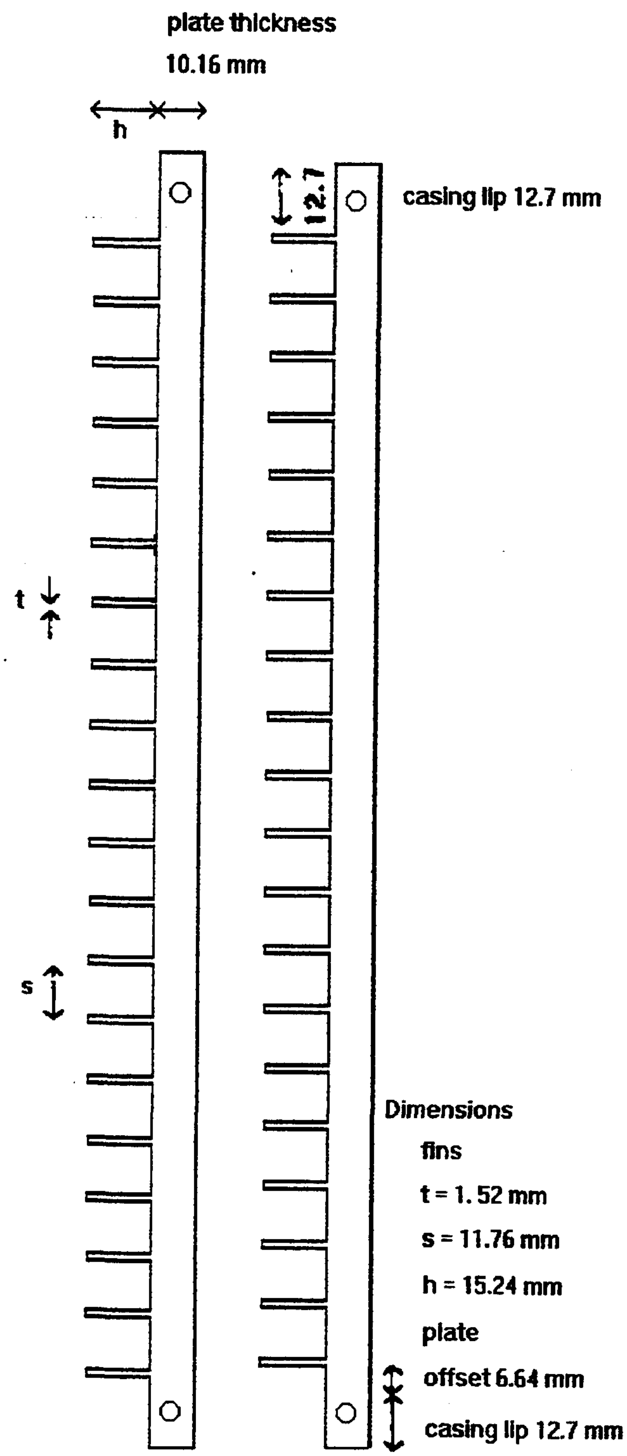


Figure 6. Finned Section Design, adapted from Ref 11, p.20.

2. Plexiglass Cover

Using the assembled plate as a template, a cover for the base and fin array assembly was fashioned using 12.7 mm (.5") thick plexiglass sheet. The sides were milled to the height of the fins (15.24 mm). The top was cut to the dimensions of the base plate, 654 mm by 260.5 mm [Ref. 11]. The sides were attached to the top piece using acrylic cement and secured with quarter-inch set screws. Since leakage was noted in prior runs, a bead of RTV was run along the joint of the side pieces and top and in each corner. The plexiglass cover was designed to fit securely over the finned array in order impede flow from crossing over the top of the fins.

3. Inlets and Outlets

Three inlets and three outlets were drilled into the axial ends of the plexiglass cover. A 3.175 mm (1/8") pipe thread was drilled and tapped into the plexiglass wall from which a 6.35 mm (1/4") Tygon tube adaptor was mounted on the outside. Valves were placed on the two outer outlets so that they could be closed when operating the test section as needed. One inlet and outlet were aligned on the longitudinal axis of the test plate. The two outer inlets and outlets were placed 379 mm from the outer edges. [Ref. 11]

4. Flow Straightener Sub-Assembly

To provide a uniform flow velocity profile, a flow straightener was devised using 38.1 mm (1.5") long straws and a plastic mesh. The mesh was to distribute the fluid flow evenly to the bank of straws that would direct the flow longitudinally. This component was placed 28 mm (1.1") away from the edge of the first fin row and 20 mm (0.8") from the inlet wall.

5. Miscellaneous Inlets

Pressure measurements were not taken in this study. For the previous study, four pressure taps with valves were installed on the longitudinal centerline of the plexiglass cover to monitor pressure drops. These penetrated the plexiglass with 1.588 mm (1/16") holes penetrating the plexiglass. Two inner taps were removed and filled in with RTV to prevent obscuring the flow visualization experiments. The outer taps, along with the outer outlets, served to eliminate entrapped air when filling the test section with liquid.

For the requirements of this study injection points and temperature probe points were drilled into the plexiglass cover. Five dye injection points were placed just after the flow straightener assembly in the inlet plenum portion of the test section. These were also 1.588 mm (1/16") holes that penetrated the plexiglass. As with the pressure tap a larger well had been then drilled centered on the smaller hole. This 3.175 mm (1/8") well was hand tapped to mount a quicklock adaptor. The dye injection assembly will be described in a later section. A 1.588 mm (1/16") OD stainless steel tubing was passed through the adaptor into the interior of the assembly.

Two temperature probe 1.588 mm (1/16") holes were placed on the centerline in the inlet and outlet plenum region of the plexiglass cover. This was deburred by hand to ensure uniformity, then filled with RTV. A five-mil Copper-Constantan thermocouple wire was feed through the hole before the setting of the RTV.

6. Temperature Instrumentation

On the bottom of the base plate fin array assembly, Copper-Constantan (T-type) cement-on thermocouples were mounted. Flat ribbon thermocouples were chosen to provide better surface contact. Placement is as seen in Figure (7). Since the thermocouples were firmly mounted and covered by a resistance heater pad, they could not be calibrated to a zero reference point. The thermocouples were mounted using a high thermal conductivity epoxy (Omegabond 101). To reduce thermal contact resistance, a small amount of thermally conductive paste was applied to the junction of each sensor. [Ref 11]

An electrical resistance heater pad was glued onto the bottom of the plate, covering most of the thermocouple junctions. The pad covered the finned area section except 9.525 mm at each end and 3.24 mm on the sides. Some bubbling and separation were noted, but the pad was not replaced, in order not to disturb the thermocouples.

7. Final Assembly

RTV sealed the base plate and fin array to the plexiglass cover. A gasket was not used since the sidewalls were not milled down to accept the use of gasket material and prevent flow over the tops of the fins. Machine setscrews were threaded to tighten the aluminum plate to the plexiglass cover. A plywood and foam rubber platform served as the base for the assembly. Additional foam rubber insulation was fitted around the sides and top to reduce heat losses to ambient atmosphere. Tygon tubing connected the fluid circulation system. The thermocouples were connected to the data acquisition system.

B. SUPPORT SYSTEMS

The support systems were identical to that used by Masterson in his thesis. Figure (8) is the overall system schematic of experimental equipment.

1. Data Acquisition System

Temperature and voltage measurements were made by a computer driven data acquisition system consisting of an HP 9000 computer controlling an HP 3852 Data Acquisition/Control unit. Two 24-channel, thermocouple compensated, high-speed multiplexed boards measured the thermocouple junction temperatures. A third 24-channel high speed multiplexed board monitored DC voltages from the flow meter, power supply and precision resistor. The HP computer was linked via an RS-232 port to an IBM compatible PC desktop, which stored the data for later computation and display.

Visual data was recorded using a Canon AE-1 35 mm camera, with two lenses: 28 mm 1:2.8 wide angle and 50 mm 1:1.8 portrait. A polarization filter reduced the reflection of light from the plexiglass into the lens. Magnification filters provided the 1x, 3x, and 7x photographs. For the dye-injection phase of the study, a video record was made with a SONY 8 mm video camera.

2. Power Distribution System

A KEPCO 0-100 V, 0-5 A power supply provided DC power to the MINCO foil backed patch. As described earlier, the heater pad was adhered to the bottom of the plate with pressure sensitive epoxy. A linoleum roller was used to ensure uniform adhesion. The heater pad was 25.4 cm by 30.48 cm, resulting in a 1116 square cm heating area, with a measured total resistance of 11.2 ± 1.1 Ω. The power supply output DC voltage was monitored along with the voltage drop across a precision resistor in series with the heater. The precision resistor was originally a 30-watt .1 ± 0.001 Ω resistor. Since the thermochromic crystals responded only at high power inputs, a 250-watt 2 ± 0.01 Ω was substituted.

Power to the heater was determined using the following relationship, where V_{heater} is the measured DC voltage across the heater, and $V_{resistor}$ the voltage drop across the precision resistor with resistance R.

$$Power = V_{heater} I_{heater} \qquad \textbf{Eqn. 2.1}$$

$$I_{heater} = I_{resistor} = \frac{V_{resistor}}{R} \qquad \textbf{Eqn. 2.2}$$

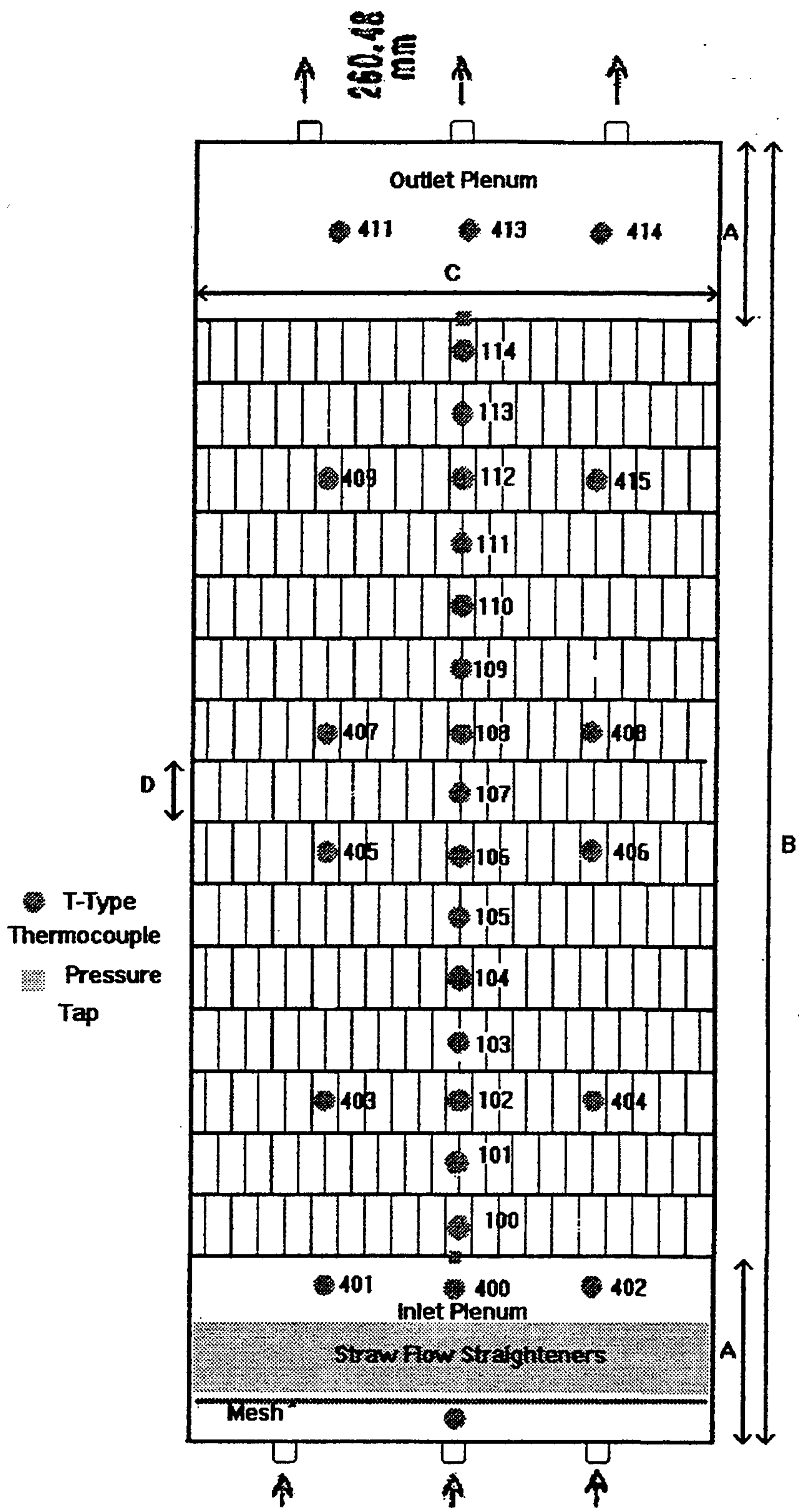


Figure 7. Test Section Top View, adapted from Ref 11. Dimensions, in millimeters, are A: 89 mm, B: 654 mm, C: 261 mm, D: 32 mm.

3. Fluid Circulation System

A regulated constant temperature bath was maintained by an ENDOCAL RTE-5 heater/refrigeration unit. This unit also provided a positive pressure fluid surge volume to a Cole-Parmer positive displacement gear type pump driven by a variable speed motor. An Omega FTB-102 turbine flow meter that used an AC-to-DC signal converter measured the fluid flow rates. Flow meter calibration consisted of a comparison of the average voltage output to the average time to collect a specific volume of water. The flow was then divided by a manifold into three flow paths: recirculation to the bath, centerline inlet, and the outer inlets coupled using a Tee-joint. A thermocouple was inserted into the center of the centerline inlet tubing by using a Tee-joint placed 2.54 cm (1") from the inlet. [Ref 11]

4. Dye-Injection System

Five taps were drilled into the plexiglass cover as described previously. The 1.588 mm (1/16") OD stainless steel surgical tubing was cut into 50 mm sections. The ends smoothed and shaped to a conic point using a motorized hand tool with a grinding stone. Each section was bent into a 90-degree bend with a turn radius of 4R, approximately the radius of a pencil. The tubing was passed through the quicklock adaptor before assembling the cover. Five 190 mm long tubes connected the adapters on the cover to a manifold. A small syringe served as an ink reservoir and provided positive pressure. The ink, printer's black, was hand injected into the flow at the different injection points.

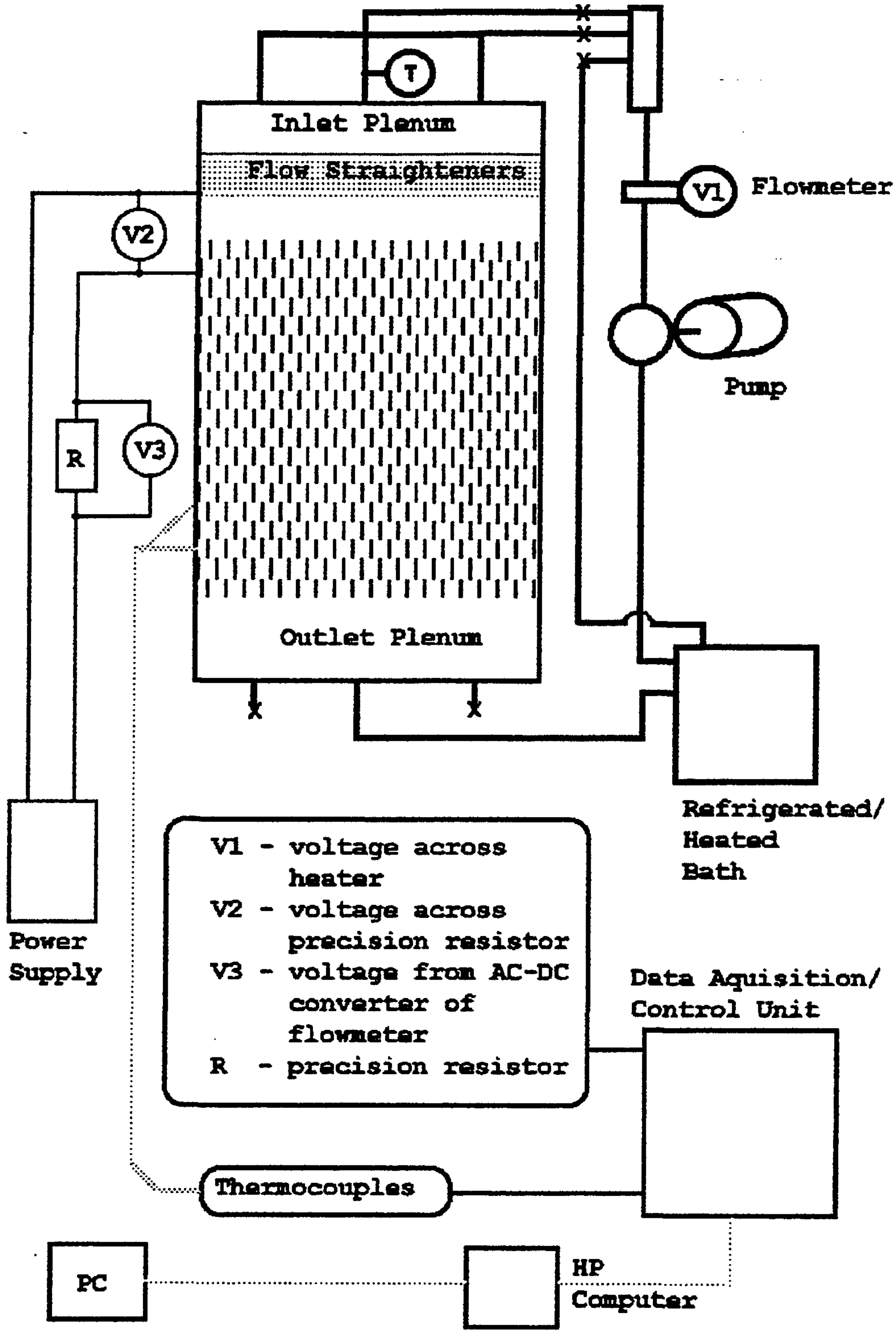


Figure 8. Overall Schematic of Experimental Apparatus, adapted from Ref 11.

C. EXPERIMENTAL PROCEDURE

The study was divided into three phases. Phase I was to recalibrate the test rig and to recreate Masterson's thesis experimental results. Phase II included the collection of new heat transfer data, and to study the response of the thermochromic liquid crystals. Flow visualization was phase III. Ink streaklines were injected into the flow to study the flow pattern through the array.

Data collection occurred at six different power settings. The flow velocity was varied by Reynolds numbers ranging from 10 to 1000. Initially a low power input was chosen to determine whether the thermocouples responded. Several refinements to the data collection programs had to be incorporated. In particular, the data collection program was coded to send a series of instantaneous readings from both the thermocouples and flowmeter to an ASCII file for further processing. These fields were then read into a spreadsheet to determine the statiscal average, mean, standard deviation and variance. Depending on the power input, the plate took about 25 to 45 minutes to reach a steady state average temperature. Therefore before taking a data run the plate was allowed to sit approximately 45 minutes before the first run. An power input ceiling of 275 watts was chosen due to precision resistor limitations. The bath temperature was maintained at 20 degrees Celsius, to mark a noted difference between inlet temperature and plate temperature.

Flow velocity was limited by the maximum pressure the plate assembly's sealant could withstand. While the pump attained a maximum capacity of 75 ml/sec, the plate assembly seals were effective only up to 53 ml/sec. Pump cavitation severely affected heat transfer measurements at high flow rates. Increasing the height of the reservoir above the pump suction decreased the incidence of cavitation only slightly.

In Phase II, it was difficult to see a response with the thermochromic crystals. To achieve any results, the bath temperature was elevated to the start temperature of the crystals. Using a high heat power input setting, the fluid flow would be varied from zero flow to approximately 60 ml/sec. When a temperature response by the liquid crystals was noted, a photograph was made. Red and blue filters were interchanged to enhance any minute change in temperature not distinguishable to the naked eye.

For the Phase III visualization, power input to the plate was minimal. The desire was to maintain the plate at a uniform temperature, but avoid any response by the liquid crystals. The liquid crystals would sometimes turn from chalky white to dark blue-black before the red start temperature, which obscured the streaklines. Fluid flow velocity was incrementally increased from zero to 70.8 ml/sec. Converted, the fin thickness Reynolds number ranged from one to 317. Still photographs and video tape ere made of the streaklines of the fluid flow through the fin array.

III. RESULTS

A. HEAT TRANSFER STUDIES

Two different Reynolds number were defined for the fluid flow analysis. The primary Reynolds number, Equation (3.1), is based on the hydraulic diameter. This is the common Reynolds number used in the heat transfer calculations. Referring to Figure (3), the hydraulic diameter, Equation (3.2), relates the cross-sectional area of a duct to its heat transfer area. Minimal cross-sectional area, in Equation. 3.3, is the fin height times the channel width. The characteristic length is the ratio, (A/l), or the heat transfer area (A) per unit channel length (l). Since the plexiglass cover is not considered a heat transfer surface, the channel length was modeled in Equation (3.4) as an uncovered channel, and includes the blunt edges of the fins in the preceding and succeeding rows [Ref 11, p.22].

$$Re_D = \frac{\rho v \cdot D_h}{\mu} \qquad \textbf{Eqn. 3.1}$$

$$D_h = \frac{4 \cdot A_c}{\frac{A}{l}} \qquad \textbf{Eqn. 3.2}$$

$$A_c = s \cdot h \qquad \textbf{Eqn. 3.3}$$

$$A = s \cdot l + 2 \cdot h \cdot l + 2 \cdot t \cdot h \qquad \textbf{Eqn. 3.4}$$

The velocity of the fluid flow through the channels is calculated by Equation (3.5) using the volummetric flow rate as measured from the flow meter. This would be the average velocity for a fully developed flow into the free frontal area of the first row.

The free flow area (A_f) is the minimal cross section area of the unit channel times the number of channels (M) in the array. There are 19 and one half channels along the first fin row.

$$v = \frac{Q}{A_f} \qquad \text{Eqn. 3.5}$$

$$A_f = M \cdot A_c \qquad \text{Eqn. 3.6}$$

To calculate the flow rate through the flow meter a linear relationship between the output voltage from the flow meter and a sampling of timed measurements was determined. When the linear regression line was compared to a cubic and a parabolic spline interpolation curves were in close agreement to the linear regression solution.

The second Reynolds number investigated was based on the fin thickness (t) as the characteristic length. This relationship was defined as:

$$Re_t = \frac{t \cdot U_o \cdot \rho}{\mu} \qquad \text{Eqn. 3.7}$$

where U_o is the average velocity in the test section inlet. The fin thickness Reynolds number was calculated to compare flow visualization results with a previous study by Xi, et al. [Ref. 9] The uniform velocity was also the flow rate through the flow meter divided by the frontal free area of the first fin row.

Fluid properties were determined using the fluid temperature (Eqn. 3.8) averaged between the plate average temperature and the fluid inlet temperature. The thermal fluid properties were linearly interpolated over the range from 20° C to 40° C from saturated water tables [Ref. 13]. The fluid inlet temperature was monitored in two locations, in the center of the centerline inlet tubing and in the centerline of the inlet plenum. The plate average temperature was the average temperature of the fifteen thermocouples used in the centerline array.

$$T_f = \frac{T_{avg} + T_{inlet}}{2}$$ **Eqn. 3.8**

$$T_{plate} = \frac{\sum_0^N T(i)}{N}$$ **Eqn. 3.9**

Power into the plate was determined using Equations (2.1) and (2.2). Both the voltage across the heater terminals and the current into the heater were measured. Since the heater dimensions remained constant, the heat flux was easily calculated. As the plate's total heat transfer capability was the focus of this phase of the study, the average Nusselt number was calculated by Equation (3.10).

$$q'' = \frac{Power}{A_{heater}}$$ **Eqn. 3.10**

$$\mathrm{N}_{avg} = \frac{h \cdot L}{k_f} = \frac{q'' \cdot D_h}{k_f \cdot (T_{avg} - T_{inlet})}$$ **Eqn. 3.11**

An experimental Colburn j Factor was calculated to relate the plate's dimensionless heat transfer coefficient to the Reynolds number. This was then compared to correlations devised by Weiting [Ref. 6], Manglik and Bergles [Ref. 8] and Joshi and Webb [Ref. 7].

$$j = \frac{N_{avg}}{Re_D \cdot Pr^{\frac{1}{3}}}$$ **Eqn. 3.12**

The following correlations predict the heat transfer as a function of fin geometry ratios and fluid flow velocity through the fins. Weiting's correlation was for a fin in air. He considered the correlation to be accurate within ±10%, though some points deviated by forty percent [Ref. 8]. Furthermore, he questioned the "applicability of the correlations to fluids outside the gas Prandtl range [Ref. 6]." For Reynolds numbers in the laminar range, he stated that the Colburn j factor was only a function of Reynolds number and the flow passage aspect ratio or the ratio of fin length to hydraulic diameter [Ref. 6].

For $Re_D \leq 1000$:

$$j = 0.483 \cdot \left(\frac{l}{D_h}\right)^{-0.162} \cdot \left(\frac{s}{h}\right)^{-0.184} \cdot Re_D^{-0.536}$$ **Eqn. 3.13**

In the turbulent region, the ratio of fin thickness to hydraulic diameter is significant [Ref. 6].

$Re_D \geq 2000$:

$$j = 0.242 \cdot \left(\frac{l}{D_h}\right)^{-0.322} \cdot \left(\frac{t}{D_h}\right)^{-0.089} \cdot Re_D^{-0.368}$$ **Eqn. 3.14**

where,

$$D_h = \frac{2 s \cdot h}{s + h}$$ **Eqn. 3.15**

Manglik and Bergles in their review of past analytical models noted a need for a single predictive equation (Eqn. 3.16) for the Colburn j factor as a function of Reynolds number from the laminar region through the fully turbulent region. They held their model to be accurate within ±20%. [Ref. 8].

$$j = 0.6522 \cdot Re_D^{-0.5403} \cdot \left(\frac{s}{h}\right)^{-0.1541} \cdot \left(\frac{t}{l}\right)^{-0.1499} \cdot \left(\frac{t}{s}\right)^{-0.0678}$$ **Eqn. 3.16**

H. M. Joshi and R. Webb developed Equations (3.17) and (3.18) to predict the heat transfer coefficient within the transition region until fully developed turbulence [Ref. 7]. They estimated their correlation to be accurate within ±20%.

For $Re_D \leq 1000$:

$$j = 0.53 \cdot Re_D^{-0.50} \cdot \left(\frac{l}{D_h}\right)^{-0.15} \cdot \left(\frac{s}{h}\right)^{-0.02}$$ **Eqn. 3.17**

$Re_D \geq Re_D + 1000$:

$$j = 0.21 \cdot Re_D^{-0.40} \cdot \left(\frac{l}{D_h}\right)^{-0.24} \cdot \left(\frac{t}{D_h}\right)^{0.02}$$ **Eqn. 3.18**

These predictive correlations were compared to the experimental value for the Colburn j Factor. These values were plotted on a semi-log chart, presented in Figure (9). The experimental data from Masterson's thesis were included for comparison. From the combination of the current data with Masterson's, a fitted linear relationship was developed. An uncertainty analysis for the Colburn j Factor is shown in Appendix A for the 275 watt power setting at 20% flowrate.

B. HEAT TRANSFER RESULTS

Two variables were chosen for data collection. These were fluid flow rate and the power input to the heater. The flow rate was varied so that the Reynolds number varied from 100 to 1000; the power input, from 100 to 275 watts. Using a spreadsheet, the arithmetic average, median, standard deviation and a variance was calculated for the approximately sixty-six data points. A sample calculation is presented in Appendix B for the 275 watt power setting at 20% flowrate. From these numerical computations, the plate average temperature, fluid temperature, flow rate and heat flux were determined. Appendix C contains the mean data for each run, with accompanying centerline distribution graphs.

Table (I) contains the final Colburn j factors as calculated using Equations (2.1 - 2.2) and Equations (3.1 to 3.12). Masterson's data is listed in Table (II) [Ref. 11]. The Colburn j factors listed in Tables (I) and (II) were then combined and plotted on the same graph, Figure (9). Masterson's data, labeled O, fell consistently above the predicted j factors, while the current data, labeled X, lands below. Plotting the zone of accuracy as published by Weiting [Ref. 6], Manglik and Bergles [Ref. 8], and Joshi and Webb [Ref. 7] show the experimental data to be just on the outer edges of accuracy.

The plate average temperature was skewed low. A linear regression of the temperature readings from thermocouples labeled 101 to 113 was made to improve the accuracy of the temperature average. Since the thermocouples were placed between the bottom of the plate and the thermofoil heater, the proximity of the thermocouple junction to the electrical resistor wires in the pad may have caused peak temperature readings. Thermocouples 103, 111 and 112 had consistently high temperature values, so where discounted in the linear regression computation.

Excessive leakage from the side of the assembly at high flow rates prevented obtaining any meaningful data at Reynolds numbers higher than Re = 1000. The best heat transfer results were at the higher power input to the heater strip, as expected. The 250W and 275 W test runs yielded more comprehendible data. These runs were repeated three times with similar results. Towards the end of the heat transfer experimental phase the first thermocouple along the centerline, 101, ceased functioning. This was compensated by averaging the side thermocouples, 402 and 403, and substituting that value into the linear regression for centerline temperature.

Re	q" (W/m^2)	δT ($^\circ$C)	Nu_{AVG}	j
950	3522	4.8	14.1	.0086
811	3228	3.3	36.9	.0187
676	1904	2.2	17.1	.0137
616	2720	1.6	33.3	.0314
613	3522	1.8	36.4	.0351
603	1878	1.8	20.0	.0180
584	3527	2.1	32.2	.0323
567	1890	2.4	15.6	.0149
565	3526	1.9	35.8	.0374
560	3524	1.8	37.6	.0396
559	3524	1.8	37.0	.0390
542	3227	3.3	36.9	.0280
499	3227	3.3	36.9	.0304
458	2720	17.9	3.0	.0038
455	3228	1.9	32.4	.0413
438	2720	17.5	3.0	.0040
39	2719	17.9	3.0	.0439

Table I. Experimental Data from Horizontal Test Section.

Re	q" (W/m^2)	δT ($^\circ$C)	Nu_{AVG}	j
211	2485	6.0	11.2	.027
224	2025	6.4	8.7	.020
245	3495	9.7	9.8	0.021
263	2485	6.0	11.3	0.022
295	1960	5.2	10.2	0.018
305	2485	5.8	11.6	0.020
322	3495	9.6	9.8	0.016
380	3505	7.9	11.9	0.017
441	3505	7.8	12.1	0.015
518	3510	7.5	12.6	0.013
563	3505	7.4	12.7	0.012
623	3505	7.3	12.8	0.011
674	3505	7.6	12.4	0.010.01
731	3515	8.0	11.7	0.009
770	3515	6.9	13.6	0.010

Table II. Horizontal Test Section Data, From Ref. [11].

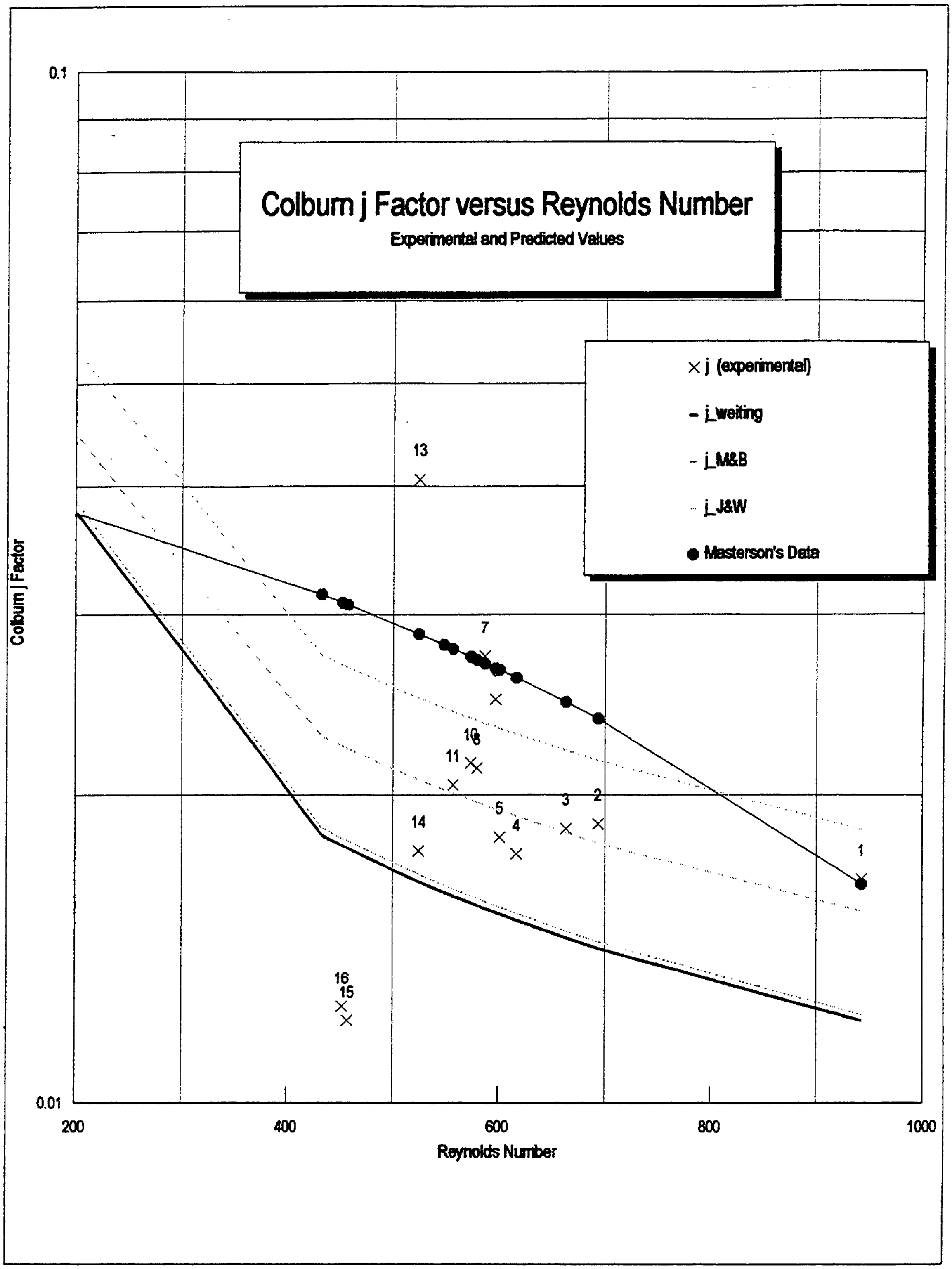


Figure 9. Colburn j Factor versus Reynolds.

C. THERMOCHROMIC LIQUID CRYSTALS

Spray-coating the plate to monitor the change in transverse and longitudinal temperatures was unsuccessful. Even though water-resistant paints were used, the crystals proved unresponsive under water. Prior test runs using air passing over the heated plate showed temperature response. The plate, with the plexiglass cover off, when heated in air to approximately 38° C changed to an even dark green color. A small fan, approximately one-third the plate width, then directed air down the plate's centerline. A color change to red (approximately 30° C) and black (below 30° C) was noted in the front central region of the plate. Transversely, the color change was abrupt, where the air flow's edge was formed by the fins. Gradually the color returned to dark green down the centerline of the plate.

This suggests that the flow of air cooled the plate until the forced air dissipated. The fins served to guide the air downstream, and blocked the air from crossing over to another channel. This also suggests the effectiveness of the thermofoil heater pad in providing uniform heating. When heated in still air, the plate showed a solid band on one side of the plate. After reaching steady state as indicated by the thermocouples, the plate was of uniform color. The red start of the crystals corresponded to 30.5° C average plate temperature.

Unfortunately these results were not to be duplicated when water passed through the array. When the plate was at low power settings, there was no change in the plate's appearance. At moderate power settings while the fluid inlet temperature was at ambient, the fins and plate bottom seemed coated with a chalky white gel. This cleared when the inlet temperature was raised to above the red start temperature of the crystals. Some crystals began to respond when the fluid temperature was raised to 40° C and the power input to the plate was maximized.

To salvage the results of this phase of the study, the plate was disassembled. A thin sheet of Mylar impregnated by the thermochromic crystals with a range of 30° to 35° C was placed on top of the fins. The plate was again heated and tested in air. Thin slices of deep blue were seen where the fin tips contacted the sheet. The remainder of the sheet was light green. As air was forced through the fins the thin slices turned green and the open region turned red to black. The effect was noted in the first three rows until the air dissipated.

When the plate was reassembled and water used as the coolant, there was better response. Entrapped air between the sheet and the plexiglass cover prevented any meaningful data concerning the water temperature and heat transfer coefficients. The sheet did indicate a temperature difference between the centerline and edge temperatures.

The best response was at the highest power setting tested, 275 watts. Flow was within the 400 Reynolds number. When the plate reached steady state, the center front and middle regions were visually light green and red. This corresponds to a surface temperature of approximately 31° C. The edges of the test assembly were a deep blue suggesting that the water was at a higher temperature than the centerline. The sheet made a rapid change to deep blue along the centerline at the fifteenth row, about three-quarters down the plate. When the flow was increased to $Re_D \approx 600$, the cooler region extended toward the end of the plate; at lower flow rates, it became shorter.

D. FLOW VISUALIZATION

Blue printer's ink injected into the fluid prior to the first fin's leading edge. This provided a flow visualization. The plate was unheated, to allow the clearest background for the ink trail. Flow was varied in five equal steps from zero to 50% power, equating to Reynolds range of 100 to 2200. This corresponds to a fin thickness Reynolds number range of 50 to 220. Photographic stills and video was taken at each flow setting. The angle of the injection tubing to the flow was also changed to place the ink streak at the fin edge and in the center of the channel.

When the ink streak was introduced at the leading edge of the fin at low flow rates, the ink followed the side of the fin. The ink did not rise perceptibly from the level of injection, about half the fin height. The ink then curled around the trailing edge of the fin, to its center. From this point, the flow carried the ink straight back through the center of the open channel until reaching the leading fin edge of the next row. After being deflected by the laminar boundary layer forming on the fin, the pattern repeated itself. This lasted throughout the first five rows of the fin array under observation.

At slightly higher fluid velocities, the flow began to waver slightly inside the third fin row. After passing the third row, the streaklines produced a more severe wavy pattern. Mixing was readily recognizable in rows four and five. Regular vortices and a turbulent wake were evident at the highest velocities. Separation with a turbulent wake was readily evident at $Re_t \approx 170$. This corresponds to the findings of Ref. (9).

IV. CONCLUSIONS

A. HEAT TRANSFER STUDIES

The experimental values come to close agreement to the predicted values. When coupled with Masterson's results, the fitted curve falls within the lower bounds of the Joshi-Webb correlation. There are some incongruities between the two data sets as seen in Figure (9). This graph shows the data from Masterson was consistently lower than predicted values. This study's current data was higher, but over a shorter range. The differences are readily explained by the inability to duplicate the previous study's data collection technique. Both exhibited the same asymptotic behavior of the predicted curve.

B. TEMPERATURE DISTRIBUTION

Since the liquid crystals did not perform as expected, very little can be gleaned as to the transverse temperature distribution. However, it is evident that the flow was not uniform across the width of plate. The visual evidence that more heat was being transferred to the fluid at the edges then the center. The effect of the channel wall may disrupt the mixing effects of the array in the centerline. Finally, the technique used to apply encapsulated crystals needed improvement, so that the crystals may be used at a solid-liquid interface.

The photographic record was inconclusive. There was some practical knowledge gained from the attempt to collect data. A more sophisticated method should be devised to include the use of thermographic films or digital recorders. The black paint backdrop also proved not conducive to clear photographs. This was especially true in the next portion of the study, flow visualization.

C. FLOW VISUALIZATION

The dye injection, while crude, effectively showed agreement with Xi, etal. The flow was fully turbulent behavior occurred at $Re_t = 170$. This equates to $Re_D = 2000$. Transition occurred approximately at $Re_D = 890$. Early transition to turbulence may have been a function of the following factors:

- scoring and burrs on the fin sides from the milling process.
- the rubber gasket between the first row and inlet plenum acting as a trip wire.
- roughness on the array's surface stemming from the spray-coating of the liquid crystals.
- vortices introduced by the flow straightener assembly.

Figure (10) is from Xi, etal. The observed flow patterns are from visual observations as recorded by photographs and video camcorder. It is difficult to reproduce the corkscrew effect seen in the midmost fin rows. Pattern (a) is at low flow rates, and is laminar as predicted. Patterns (b), (c) and (d) show increasing turbulent flow. Finally pattern (e) is fully turbulent flow.

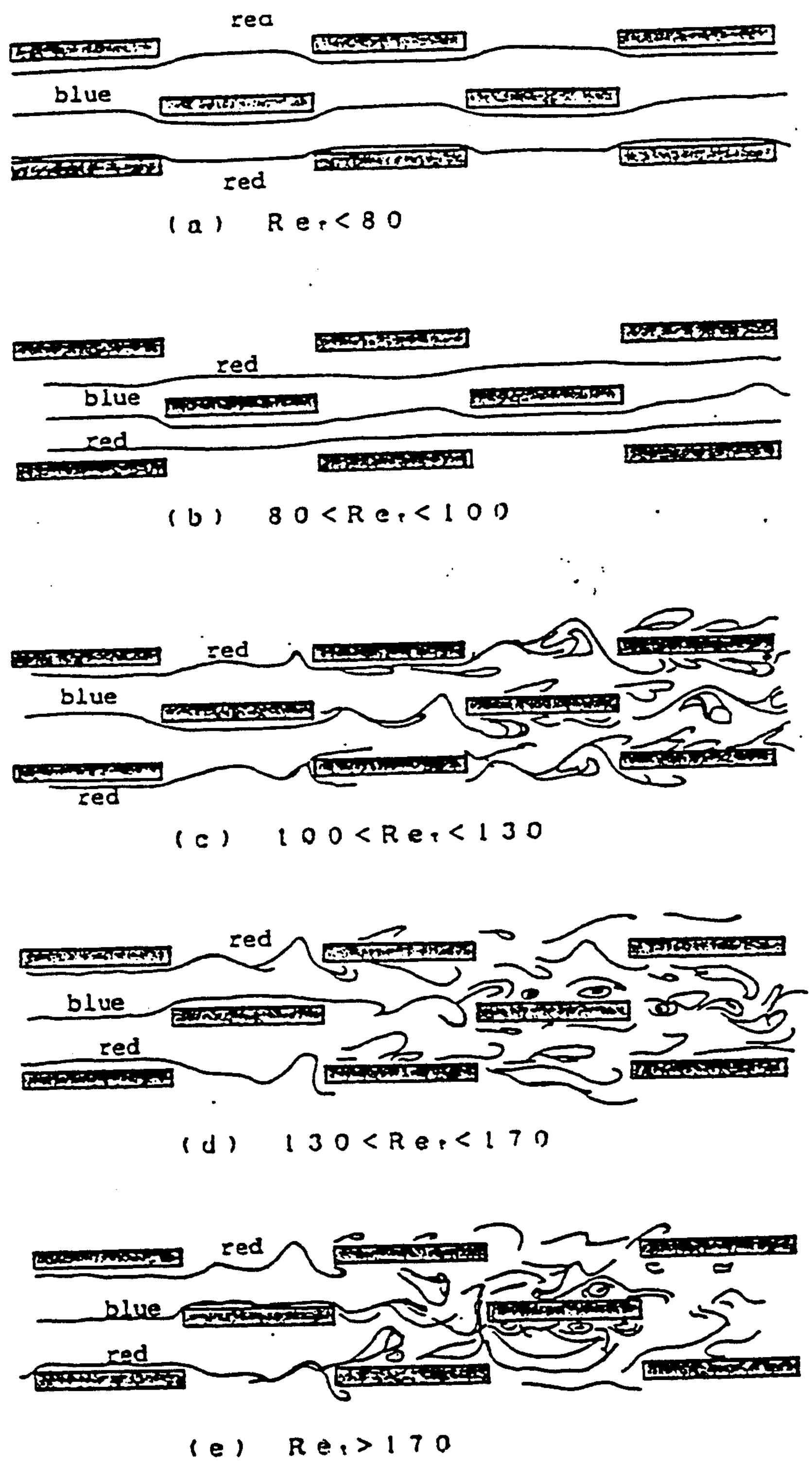


Figure 10. Flow patterns transcribed from visual observations based on format used in Ref. 9.

V. RECOMMENDATIONS

In any continuation of this study, the following additional work is recommended.

- Redesign and manufacture a new removable cover for the plate fin array. The use of an O-ring seal or other type of gasketing will be essential if PAO or other dielectric fluids are to be used.

- Attach the liquid crystal impregnated Mylar sheet on the plexiglass cover itself. The plexiglass cover should have a frame to allow changing the sheet to investigated a different temperature range.

- Investigate the use of spray-coating liquid crystals with a lower redstart temperature. One focus would be whether the crystals have a quick enough response time to notice any local temperature variations caused by the turbulence.

- Conduct the experiment using heated air as the working fluid to investigate the local temperature changes in the fin channel and fin surfaces at each row.

- Further consolidate the research to correlate data from the heat transfer studies on the external Flow-through-module assembly.

APPENDIX A. UNCERTAINTY ANALYSIS

An uncertainty analysis is provided to evaluate the accuracy of the data collected. The uncertainty function, $F = F(X_1,X_2,X_3)$, where X_i are the independent measurements is calculated by:

$$\delta F = \sqrt{(\frac{\partial F}{\partial X_1}\cdot\delta X_1)^2 + (\frac{\partial F}{\partial X_2}\cdot\delta X_2)^2 + (\frac{\partial F}{\partial X_3}\cdot\delta X_3)^2}$$

Eqn. A.1

For $F = C\, X_1^{\ a}\, X_2^{\ b}\, X_3^{\ c}$, uncertainty takes the following form:

$$\frac{\delta F}{F} = \sqrt{(a\cdot\frac{\partial X_1}{X_1})^2 + (b\cdot\frac{\delta X_2}{X_2})^2 + (c\cdot\frac{\delta X_3}{X_3})^2}$$

Eqn. A.2.

1. Reynolds Number Uncertainty

$$Re_D = \frac{\rho\, v\cdot D_h}{\mu}$$

Eqn 3.1

here

$$\frac{\delta Re}{Re} = \sqrt{(\frac{\delta v}{v})^2 + (\frac{\delta D_h}{D_h})^2}$$

and

$$\frac{\delta D_h}{D_h} = \sqrt{\left(\frac{\delta A_c}{A_c}\right)^2 + \left(\frac{\delta(\frac{A}{l})}{\frac{A}{l}}\right)^2}$$

The geometric dimensions and fluid thermal properties with uncertainty of measurement.

Plate Dimensions	Uncertainty
A_c = 0.0001792 m^2	
A = 0.001387 m^2	
l = 0.03175 m	δl = 0.5 mm
s = 0.01175 m	δs = 0.5 mm
t = 0.00152 m	δt = 0.5 mm
h = 0.01524 m	δh = 0.5 mm
Fluid Properties [Ref. 13]	δv = 0.004 m/s
ρ = 993.8 kg/m3	
T_f = 308.4 K	
k_f = 0.6254 watt/m*K	
μ = 718.7 x 10^{-6} N*sec/m2	

Calculated Uncertainties

δA_c = 9.62 E-06 m

δA = 0.0005 m

δ(A/l) = 707 E-06 m

δD_h = 920 E-06 m

D_h = .0164 m

Substituting into above yields

$$Re_D = 123 \pm 9$$

Therefore the uncertainty $\delta Re/Re = 0.073$ or 7.3%.

2. Colburn j Factor Uncertainty

$$j = \frac{N_{AVG}}{Re_D \cdot Pr^{\frac{1}{3}}}$$

and

$$\frac{\delta j}{j} = \sqrt{\left(\frac{\delta N}{N}\right)^2 + \left(\frac{\delta Re}{Re}\right)^2}$$

where

$$N_{AVG} = \frac{q'' \cdot D_h}{k_f \cdot (T_{avg} - T_{inlet})}$$

and

$$q'' = \frac{Power}{A_H}$$

$$A_h = W \cdot L$$

$$Power = V_{heater} \cdot \left(\frac{V_{resistor}}{R}\right)$$

W = 0.0254 m $\qquad$ δW = 0.0005 m

$L = 0.0305$ m

$T_{AVG} = 32.12^{\circ}$ C

$T_{Inlet} = 34.34^{\circ}$ C

$\delta L = 0.0005$ m

$\delta A_H = 0.012$ m^2

$\delta T = 0.034^{\circ}$ C

$\Delta T = 1.78 \pm 0.034\ ^{\circ}$C

$A_H = 0.07742 \pm .012$ m^2

Power $= 272.7 \pm .001144$ W

$q'' = 3522 \pm 0.095$ W/m^2

$Re = 613 \pm 43.5$

$Pr = 4.860$

Therefore,

$$Nu_{AVG} = 51.87 \pm 3.1$$

$$j = 0.03506 \pm 0.00324$$

The uncertainty $\delta j/j = 0.0924$ or 9.2%. This is well within the 10% accuracy range predicted by both the Joshi-Webb and Weiting correlations.

APPENDIX B. SAMPLE CALCULATIONS

The following calculation is for the following setpoint.

$Q = (V_1 - 0.392) \times 166.11$

Power = 272.68 watts

$T_{AVG} = 36.12^\circ$ C

$T_{Inlet} = 34.34^\circ$ C

1. Characteristic Dimension

$A_c = s*h = (11.75 \text{ mm})(15.24 \text{ mm})$

$A_c = 179.1 \text{ mm}^2$

$A = s*l + 2*h*l + 2*t*h$

$A = (11.75 \text{ mm})(31.75 \text{ mm}) + 2*(15.24 \text{ mm})(31.75 \text{ mm})$
$\quad + 2*(1.52 \text{ mm})(15.24 \text{ mm})$

$A = 1387.1 \text{ mm}^2$

$A/l = (1387.1 \text{ mm}^2)/(31.75 \text{ mm}) = 43.69 \text{ mm}$

$A_f = M*A_c = (19.5)(179.1 \text{ mm}^2)$

$A_f = 3492.4 \text{ mm}^2$

$D_h = 4*A_c / (A/l) = 4*(179.1 \text{ mm})/(1387.1 \text{ mm}/31.75 \text{ mm})$

$D_h = 16.39 \text{ mm}$

2. Water Properties

$T_f = (T_{AVG} + T_{Inlet})/2 = (36.12 + 34.34)/2 + 273.15 \text{ K}$

$T_f = 308.2 \text{ K}$

Using Table A.6 [Ref. 13]

$\rho = 993.8$ kg/m3

$k_f = 0.6254$ watt/m*K

$\mu = 718.7 \times 10^{-6}$ N*sec/m2

$\Delta T = T_{AVG} - T_{Inlet} = 36.12 - 34.24 = 1.78 \text{ K}$

3. **Reynolds Number**

$$Re_D = \rho\, vD_h / \mu$$

$$= \frac{(993.8 \text{ kg/m}^3)(5.428 \text{ E-03 m/sec})(0.01639\text{m})}{(718.7 \text{ E-06 N sec/m}^2)}$$

$$= 123.1$$

4. **Nusselt Number**

$$q" = \text{Power}/A_h = (272.68 \text{ watt})/(774.2 \text{ cm}^2)$$

$$q" = 0.352 \text{ watt/cm}^2$$

$$Nu_{AVG} = q" * D_h/(k_f*\Delta T)$$

$$Nu_{AVG} = (0.352 \text{ watt/cm}^2)(0.01639 \text{ m})/(0.6254 \text{ watt/m K})(1.78 \text{ K})$$

$$= 51.87$$

5. **Colburn j Factor**

$$j = Nu_{AVG}/(Re_D\, Pr^{1/3}) = (51.87)/(123.1)(4.808)^{1/3}$$

$$j = 0.250$$

APPENDIX C. HEAT TRANSFER DATA COLLECTION

A. Centerline Temperature Distribution

1. Figures 11 through 32.

Centerline Temperature distribution graphs for each power setting and flow rate.

B. Thermocouple Data

1. Figures 33 through 53.

Thermocouple data collected at each power setting and flowrate. This data was placed on a spreadsheet to determine average, maximum, minimum, standard deviation and variance for each thermocouple.

C. Colburn j Factor

1. Spreadsheet for Colburn j Factor

Using the equations shown in chapters two and three the following are the results used to plot the Colburn j Factor graph, Figure 9.

Centerline Temperature Distribution

Figures 11 through 32

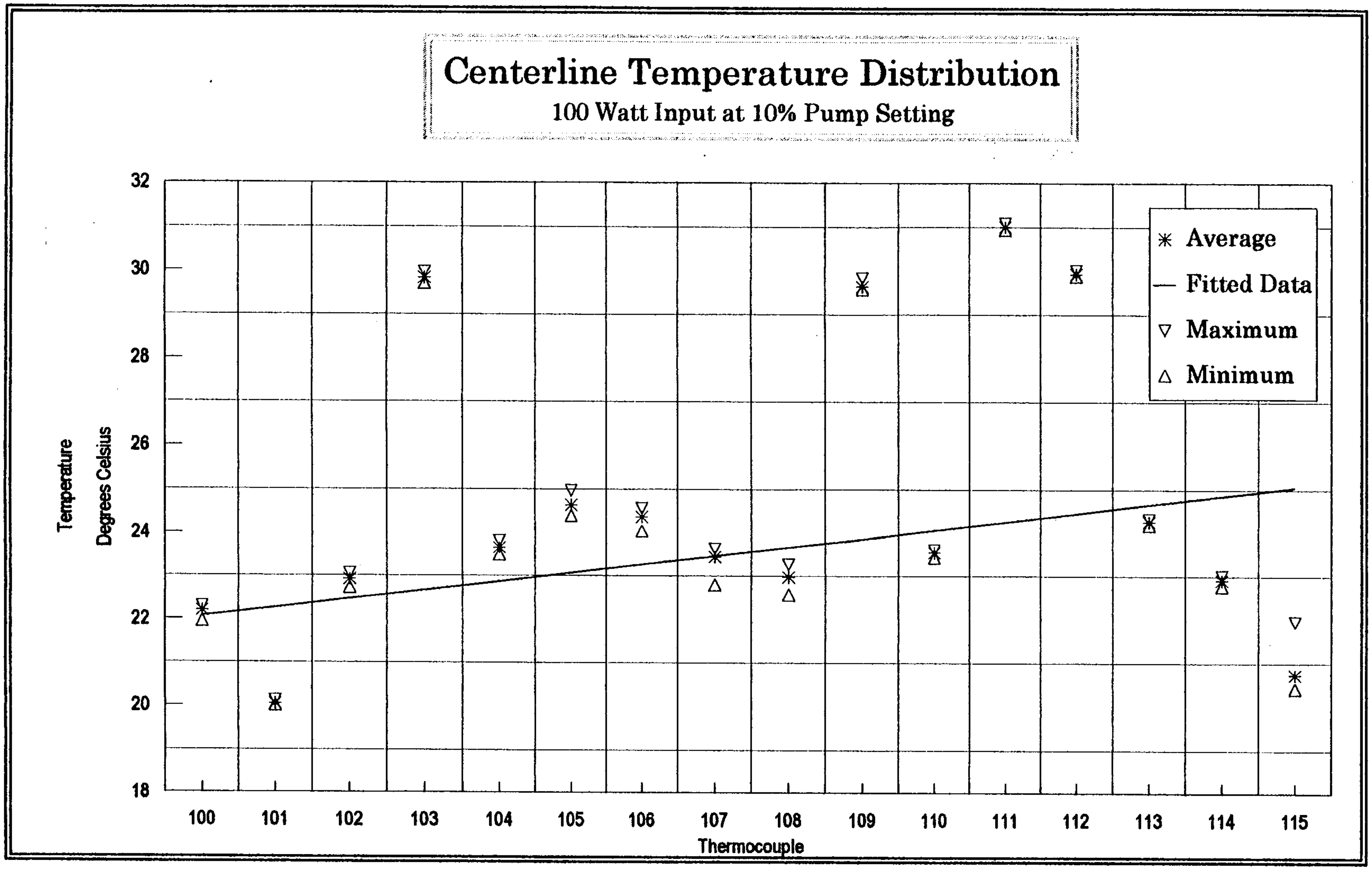


Figure 11. 100 Watts Heat Input at 10% Flow Rate

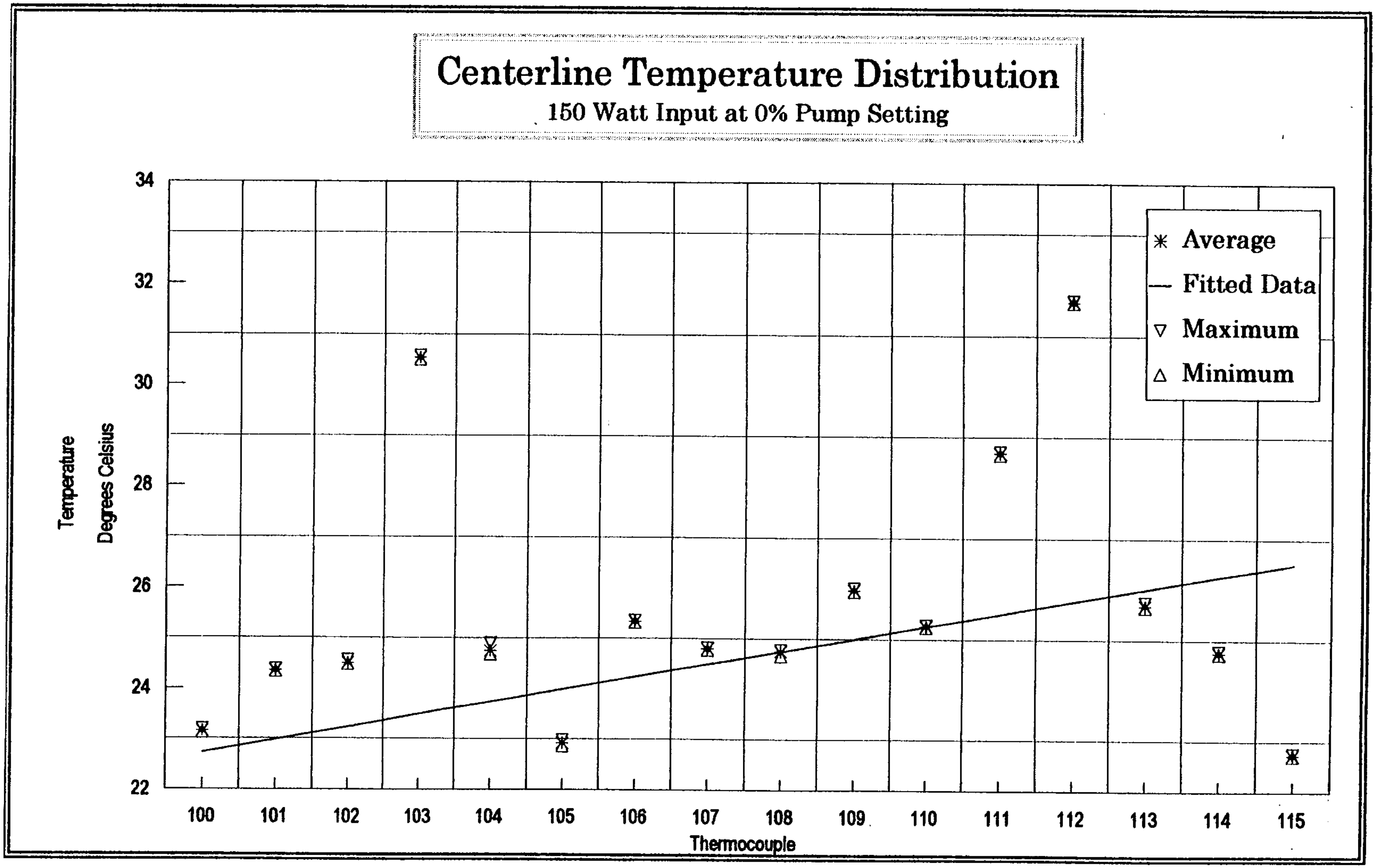


Figure 12. 150 Watts Heat Input at 0% Flow Rate

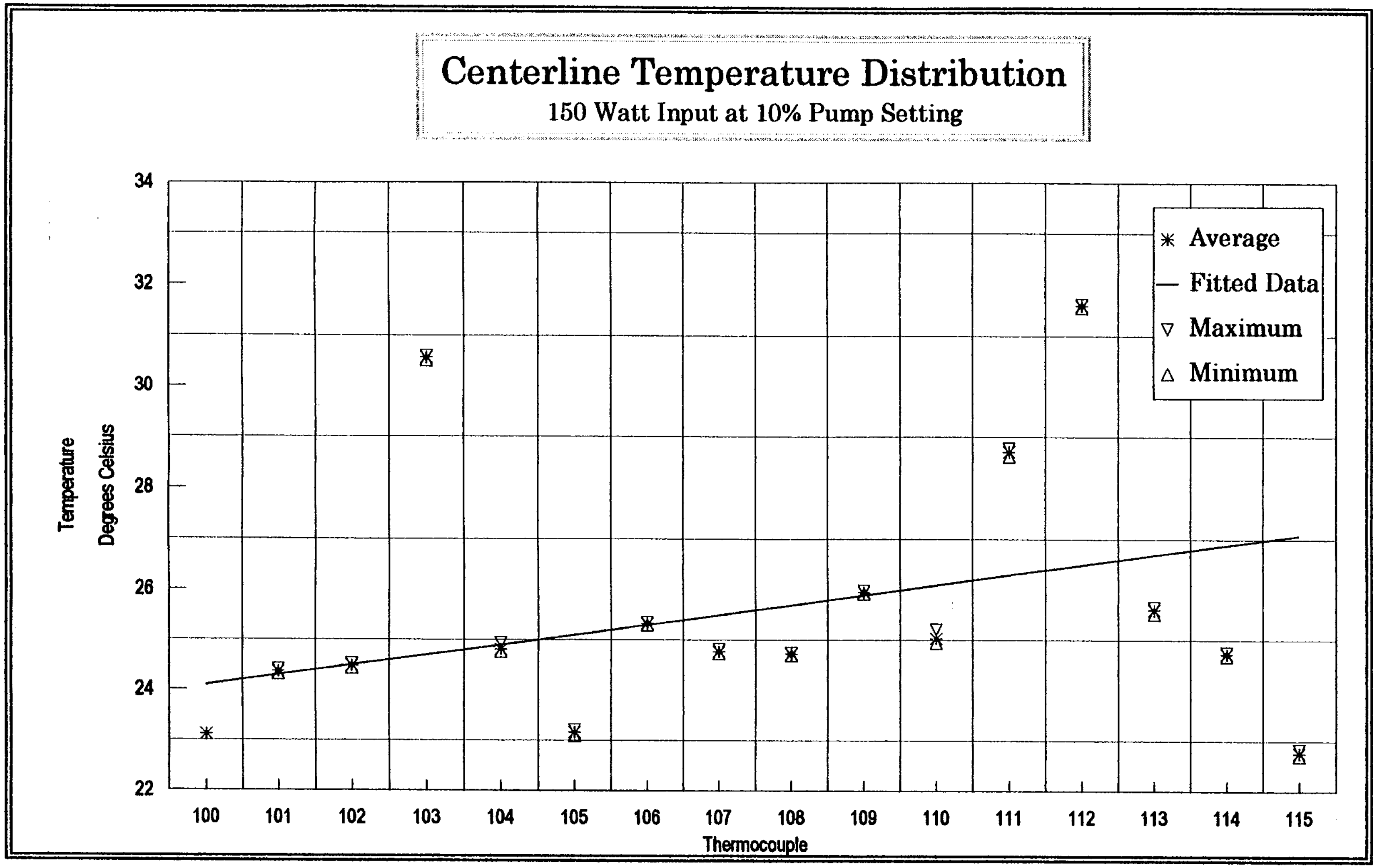


Figure 13. 150 Watts Heat Input at 10% Flow Rate

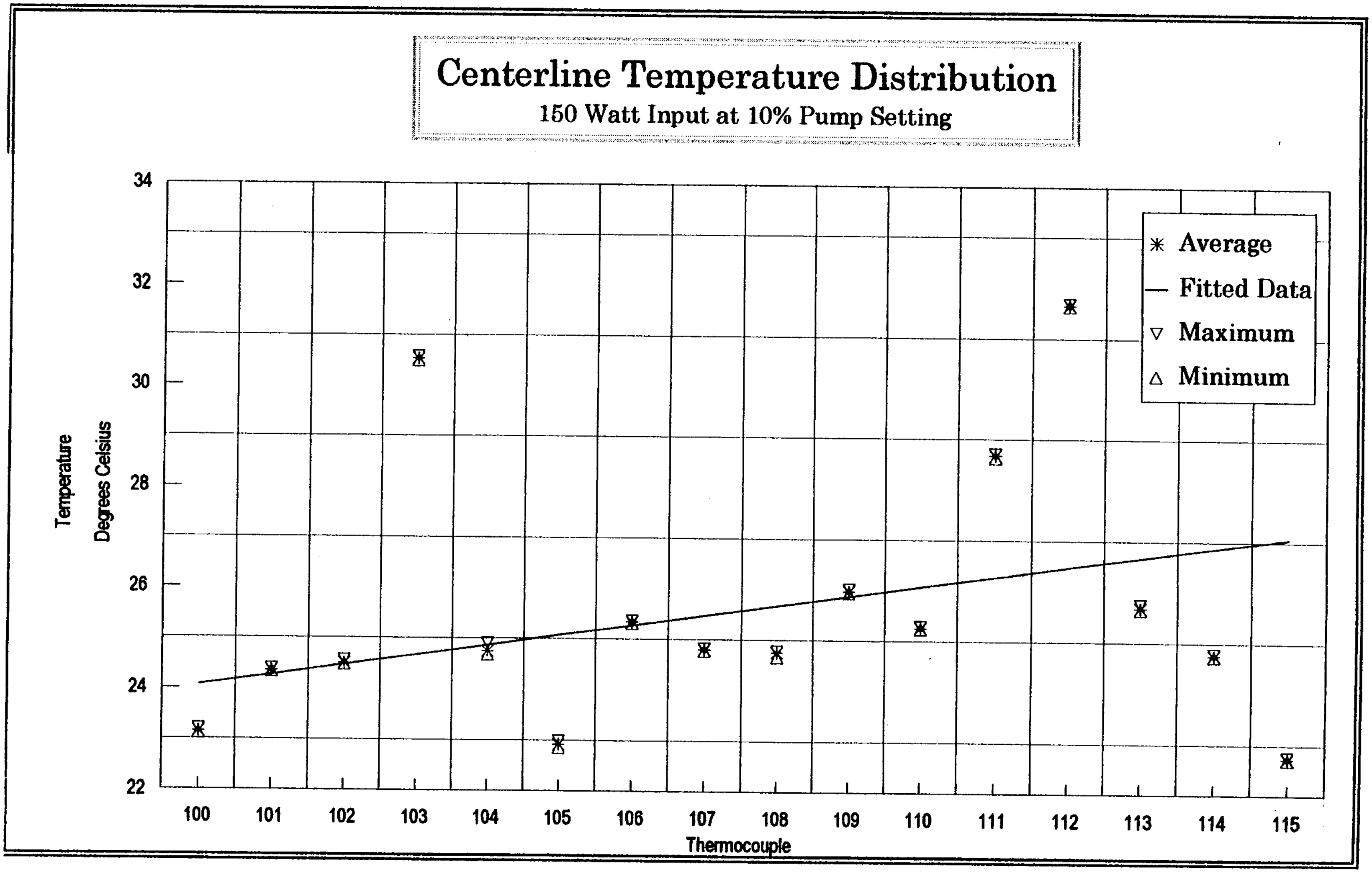


Figure 14. 150 Watts Heat Input at 20% Flow Rate

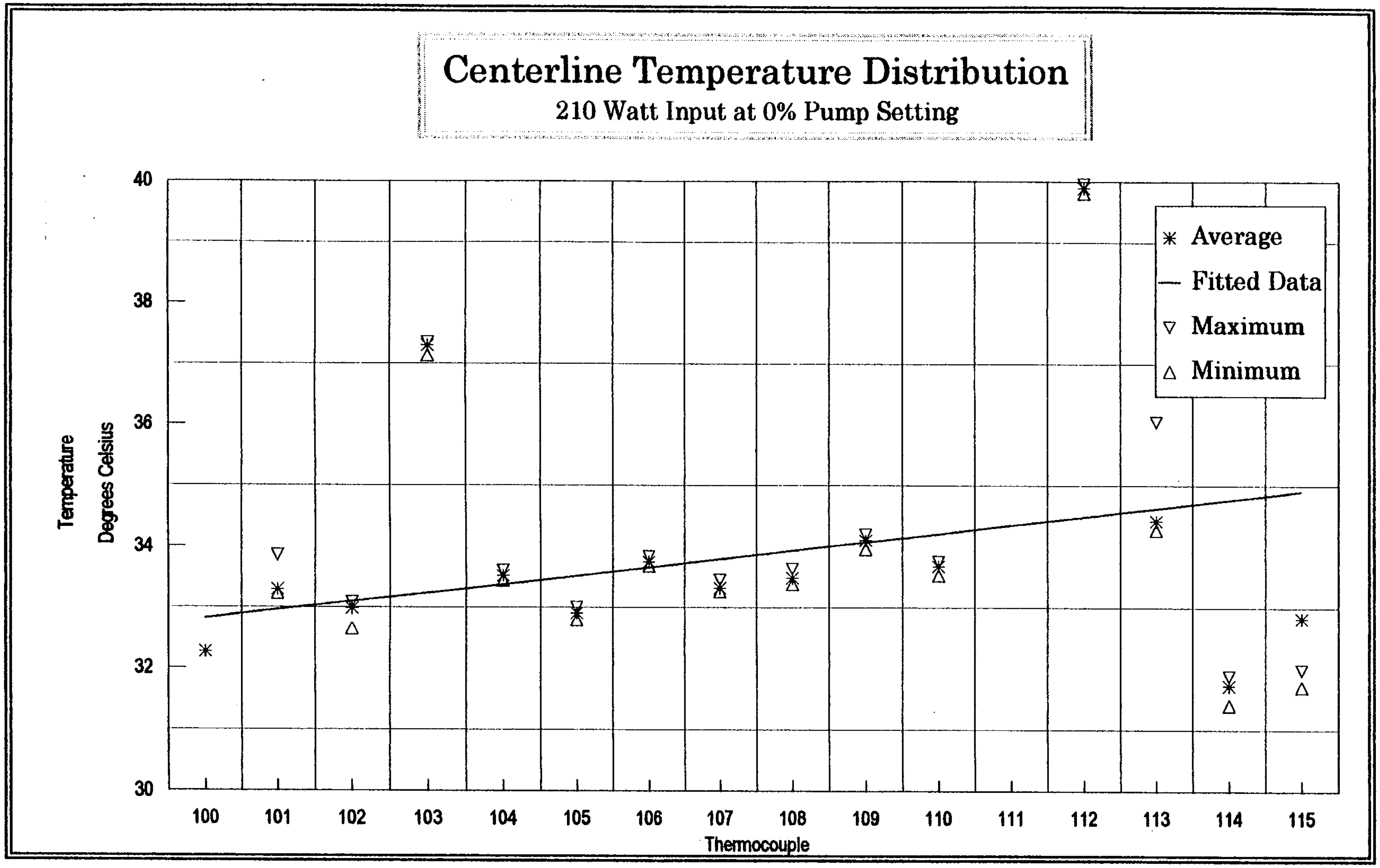


Figure 15. 210 Watts Heat Input at 0% Flow Rate

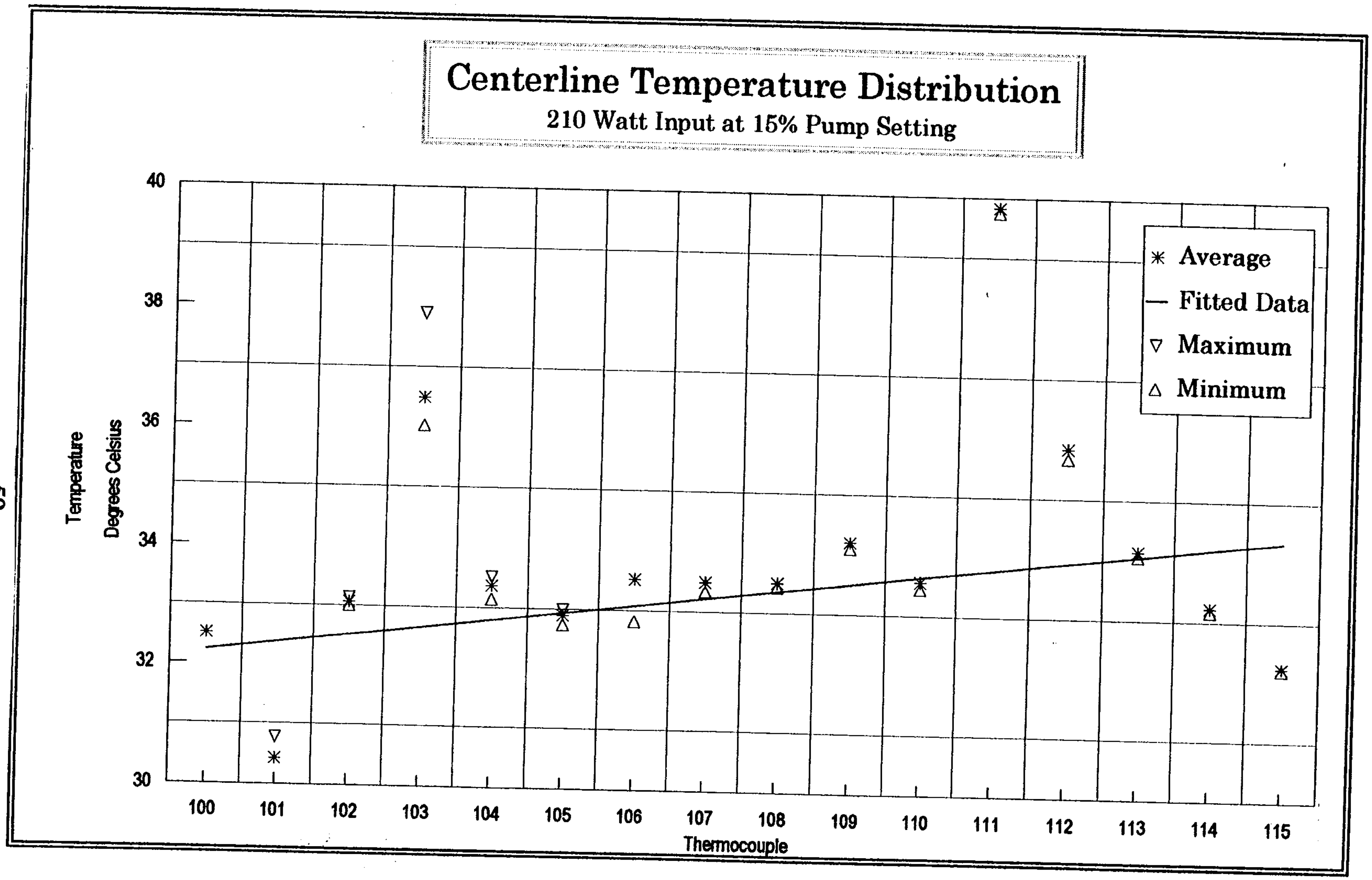


Figure 16. 210 Watts Heat Input at 15% Flow Rate

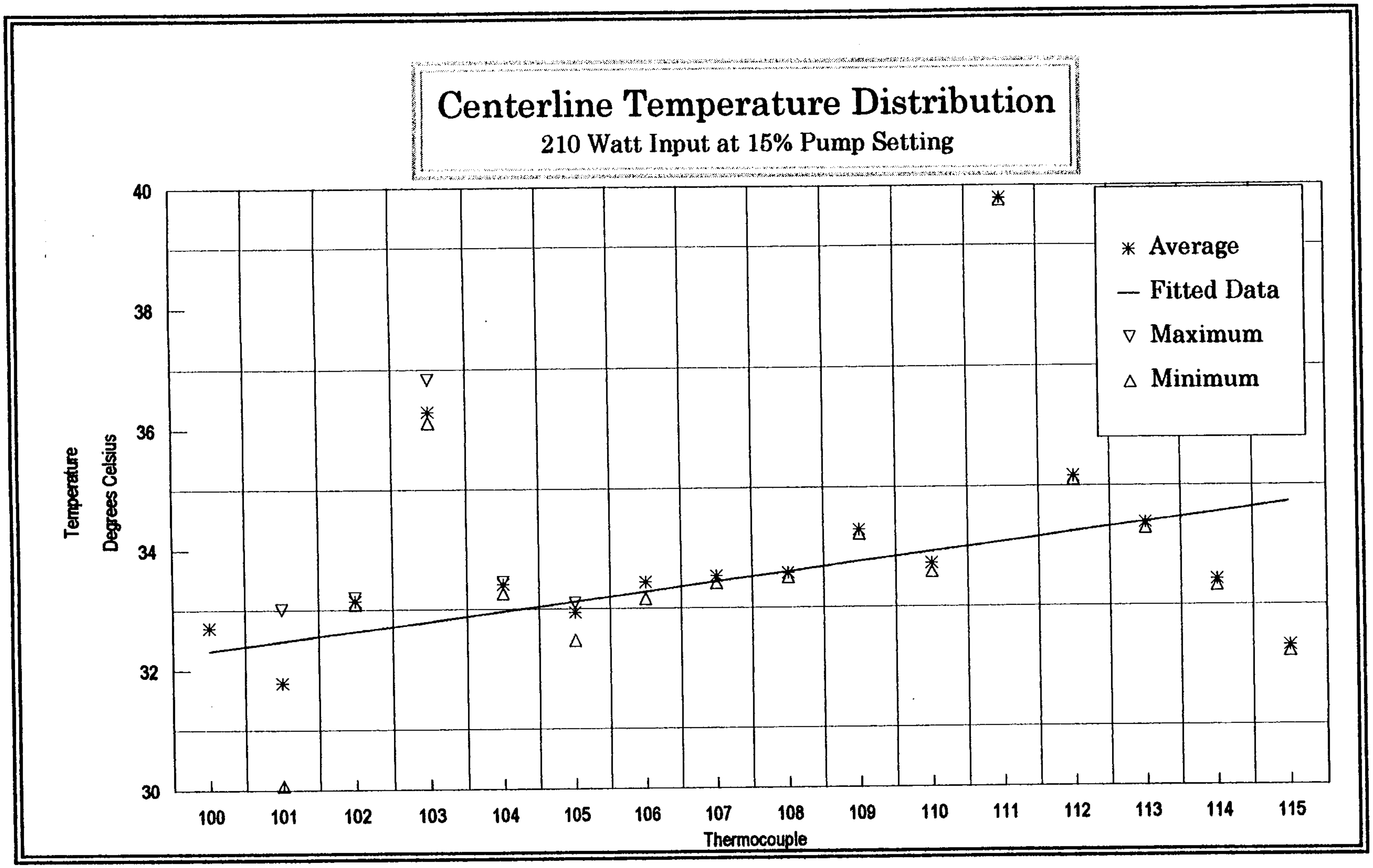


Figure 17. 210 Watts Heat Input at 15% Flow Rate

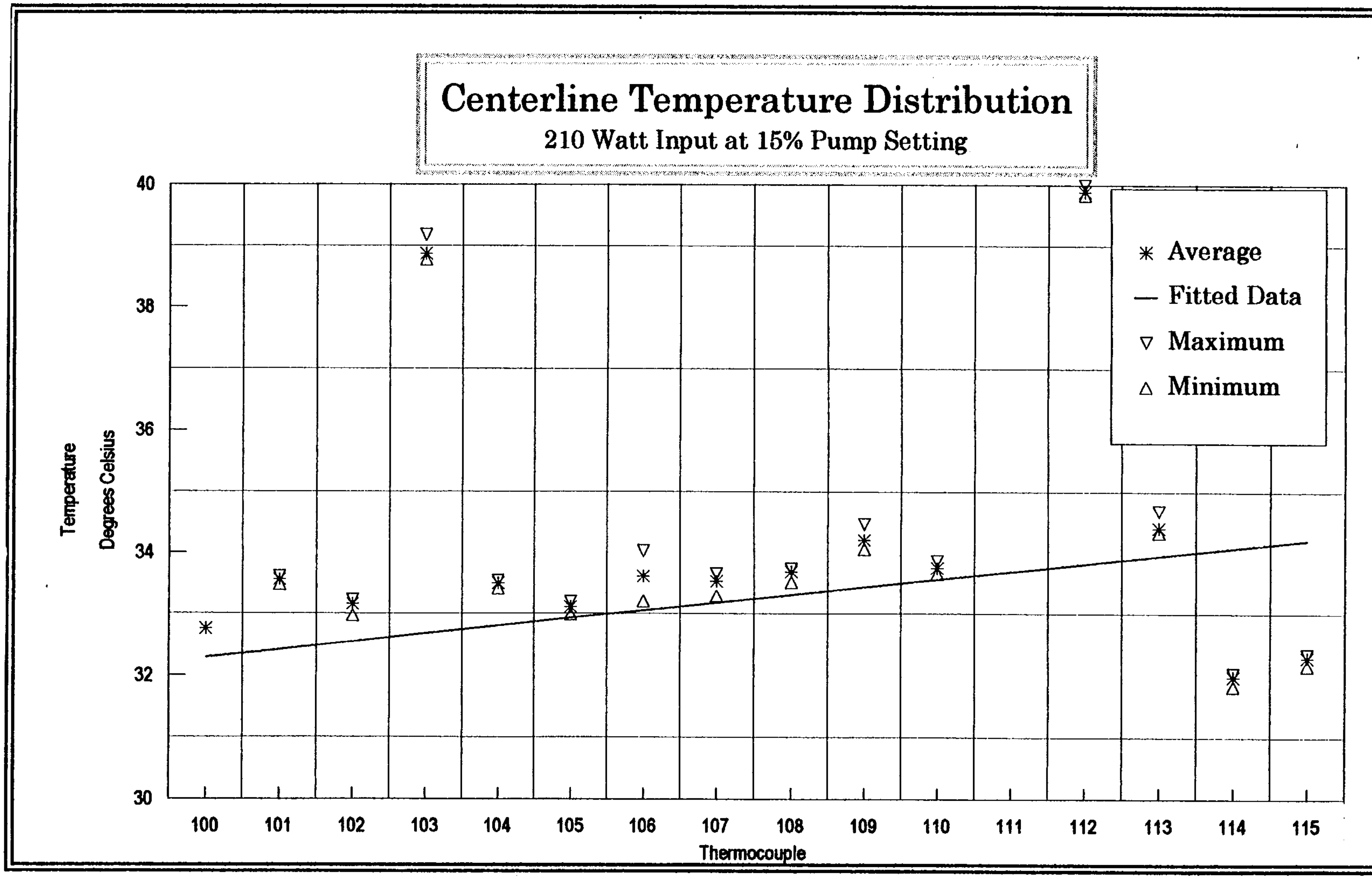


Figure 18. 210 Watts Heat Input at 15% Flow Rate

Comparison of Three Data Runs

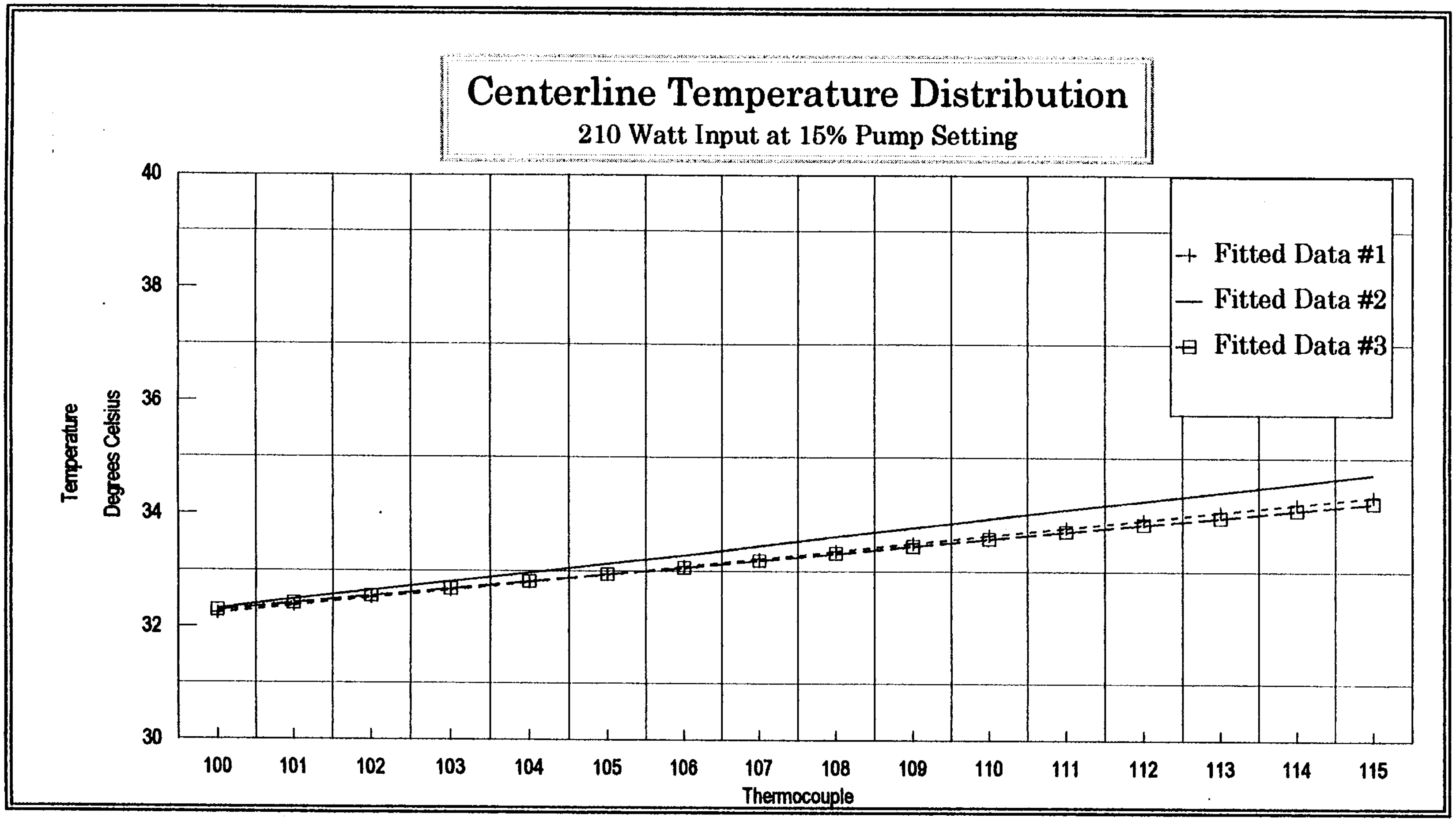


Figure 19. 210 Watts Heat Input at 15% Flow Rate

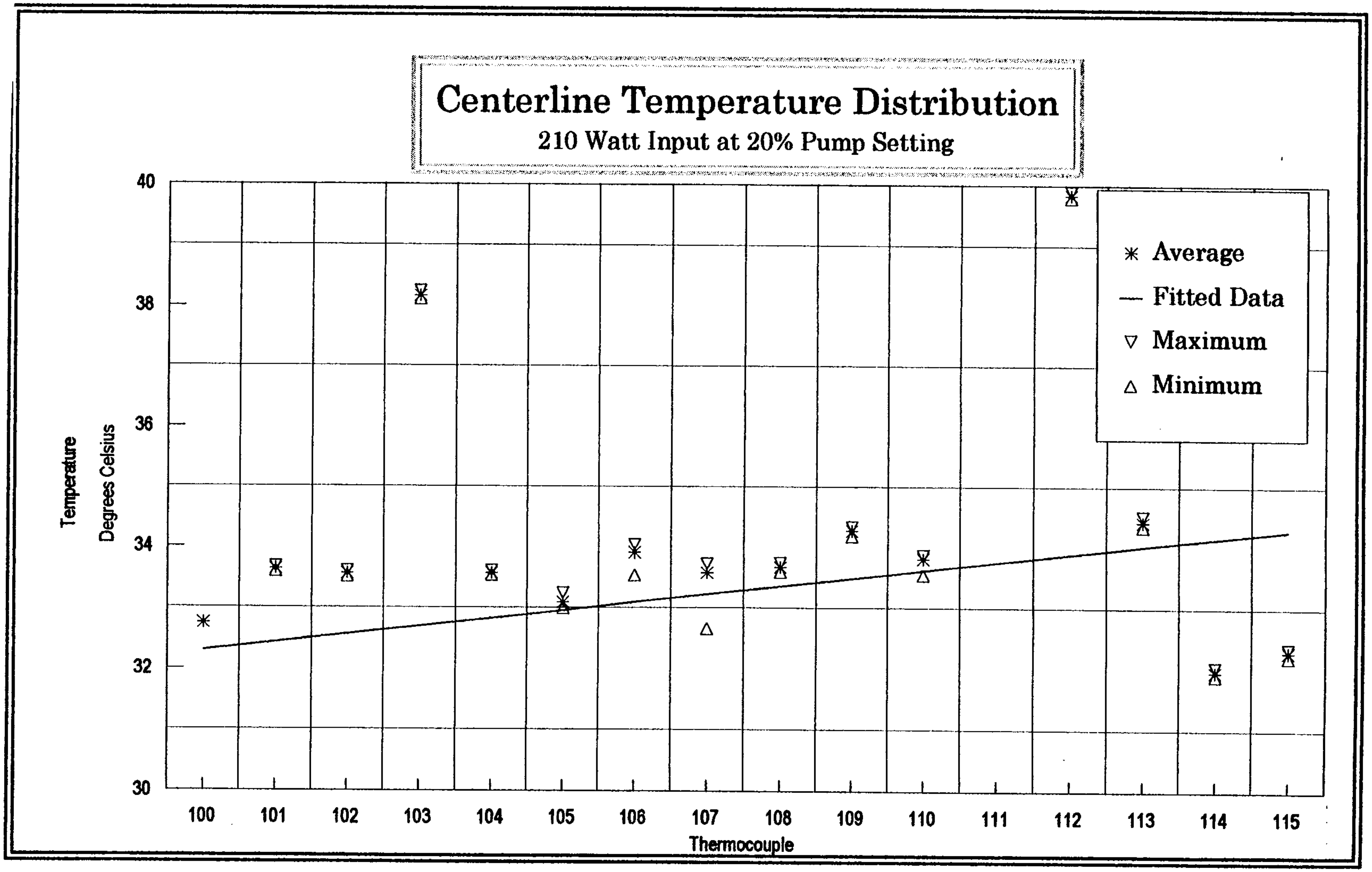


Figure 20. 210 Watts Heat Input at 20% Flow Rate

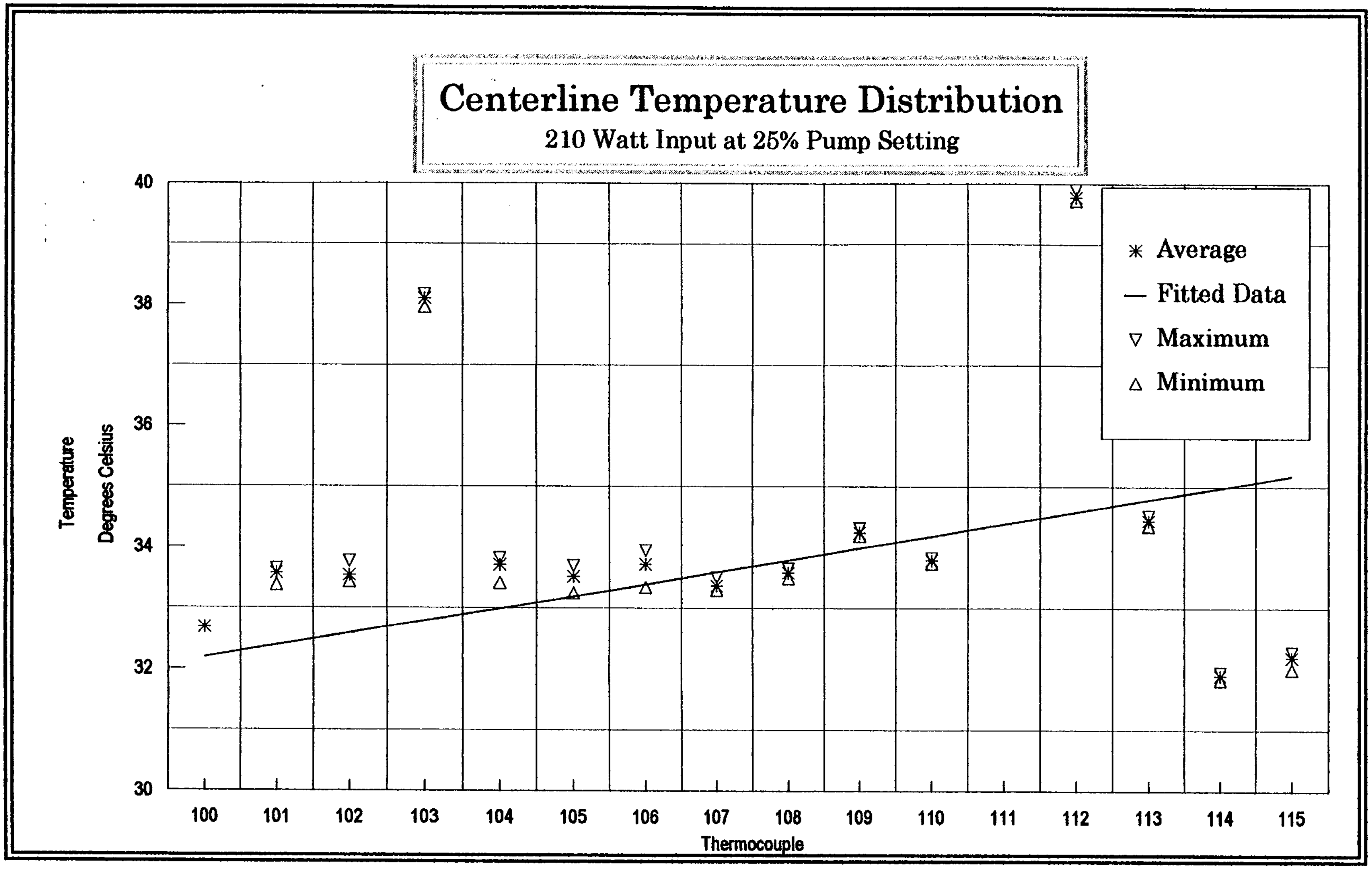


Figure 21. 210 Watts Heat Input at 25% Flow Rate

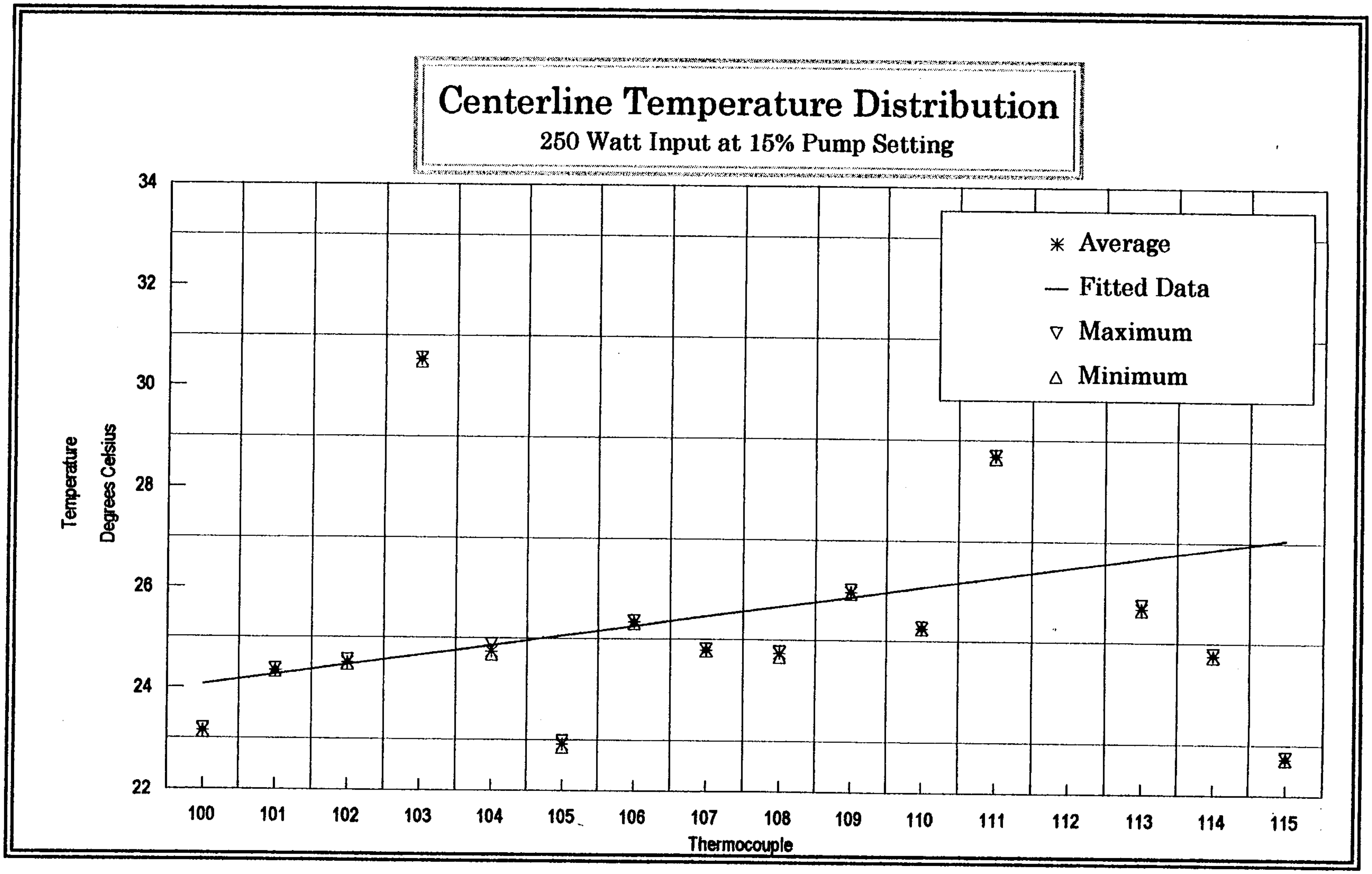


Figure 22. 250 Watts Heat Input at 15% Flow Rate

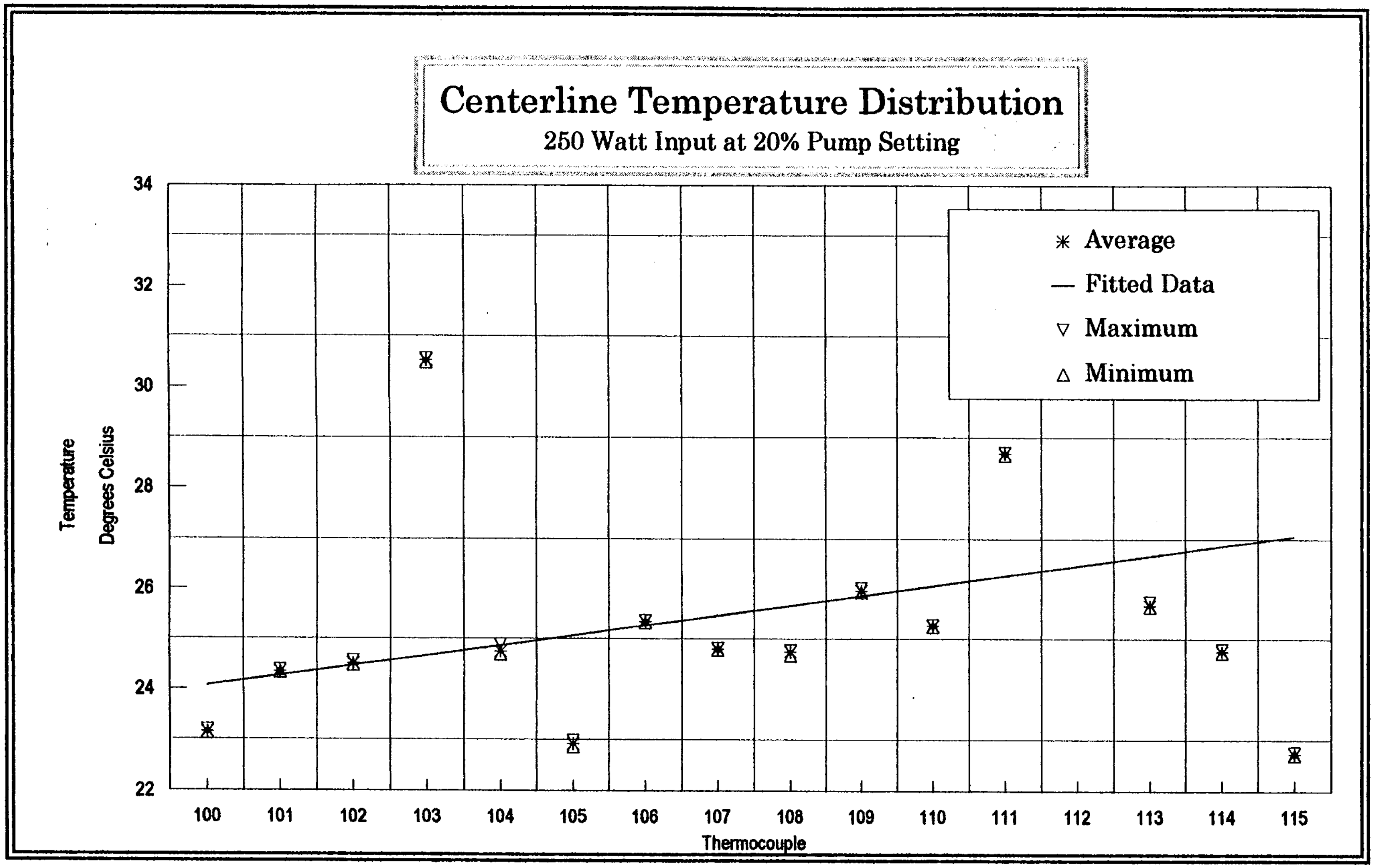


Figure 23. 250 Watts Heat Input at 20% Flow Rate

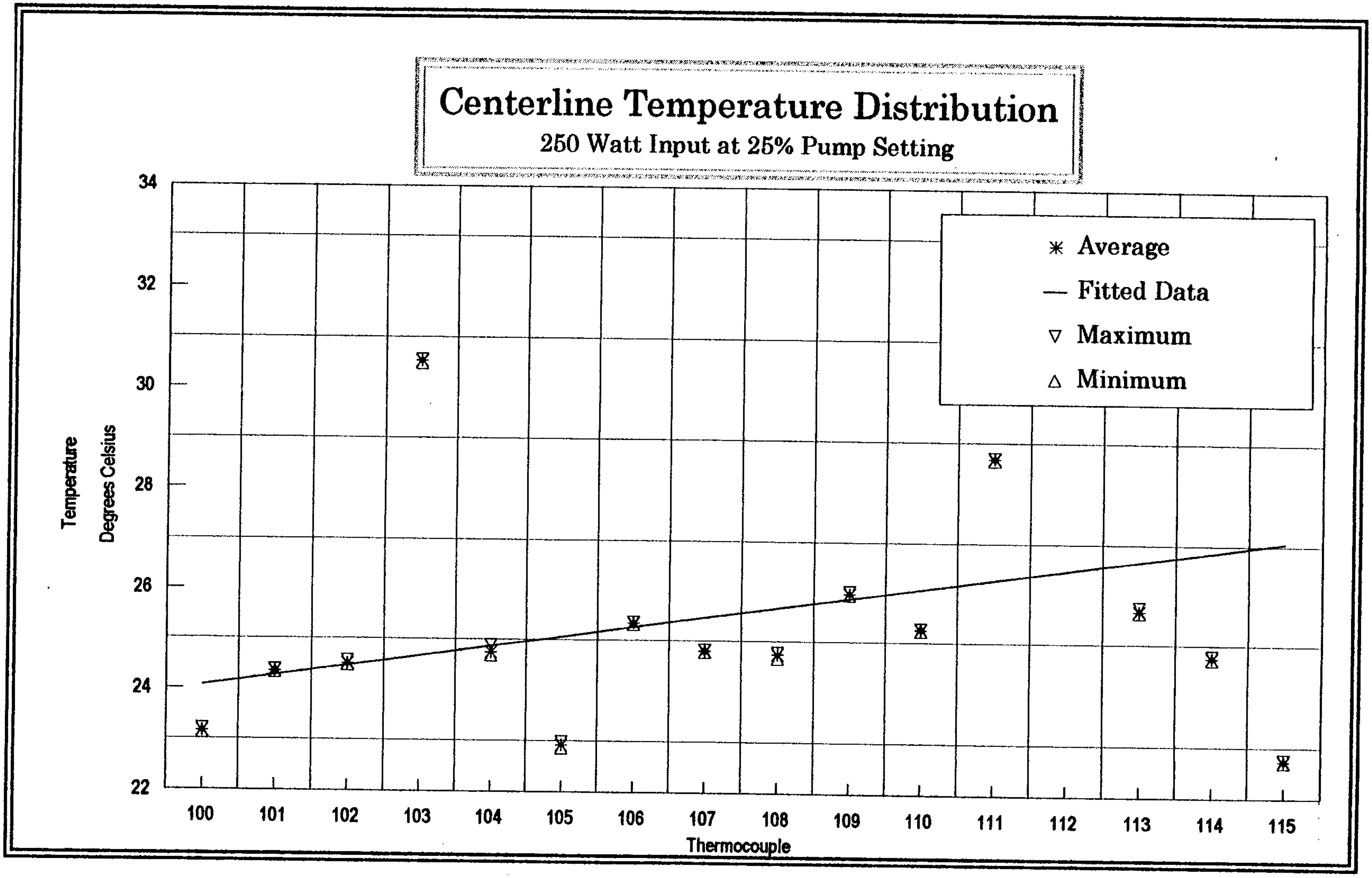


Figure 24. 250 Watts Heat Input at 25% Flow Rate

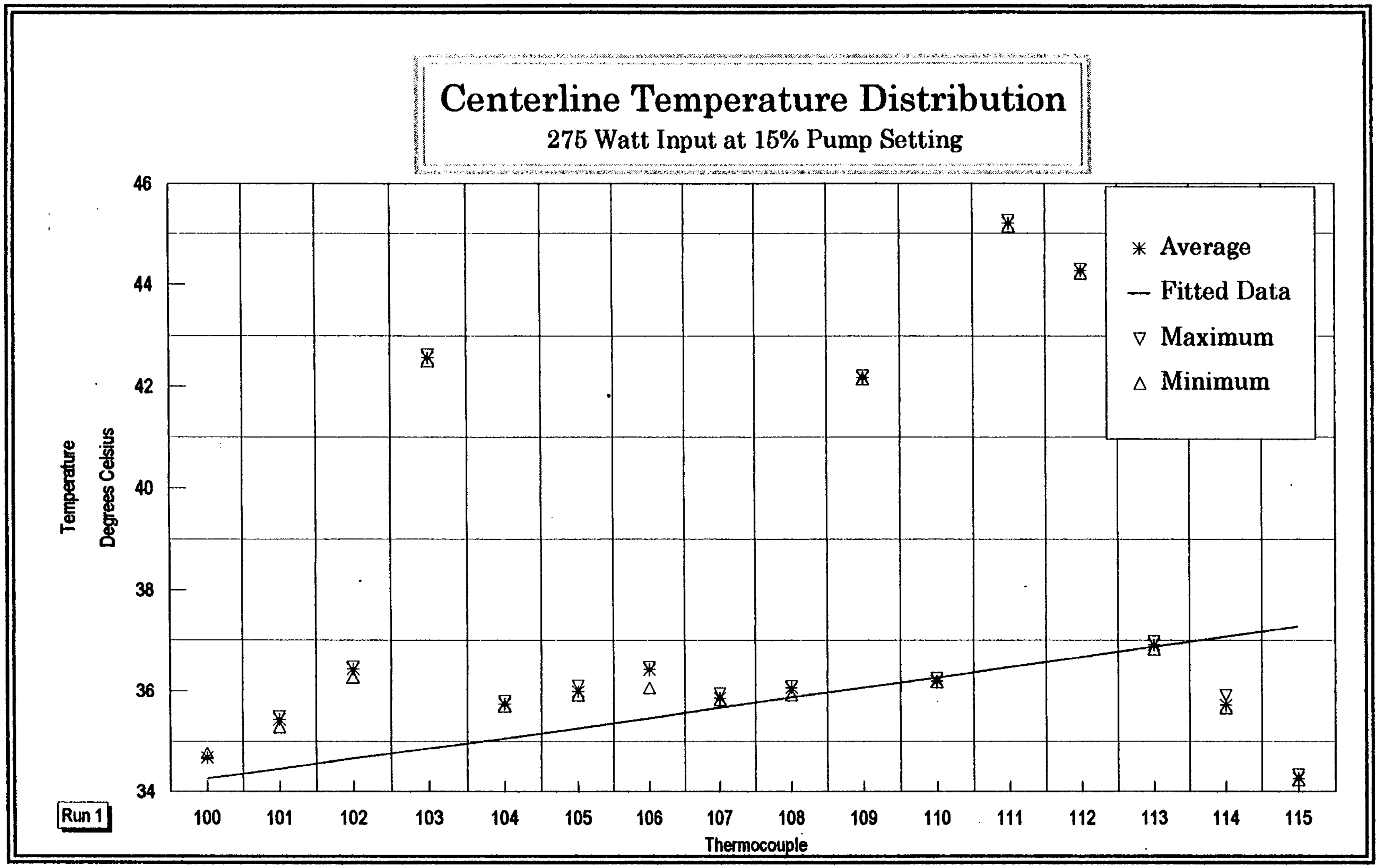


Figure 25. 275 Watts Heat Input at 15% Flow Rate

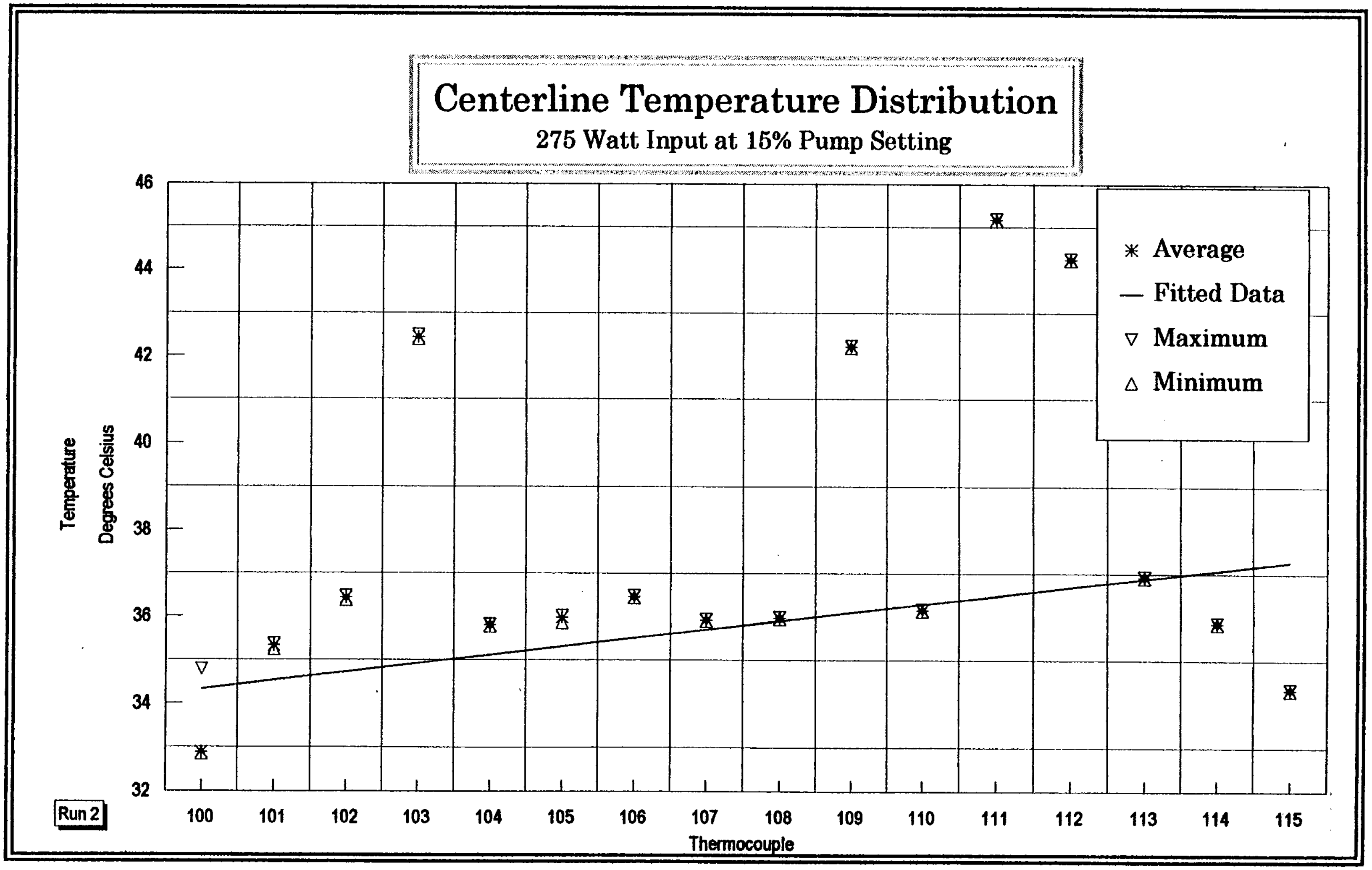


Figure 26. 275 Watts Heat Input at 15% Flow Rate

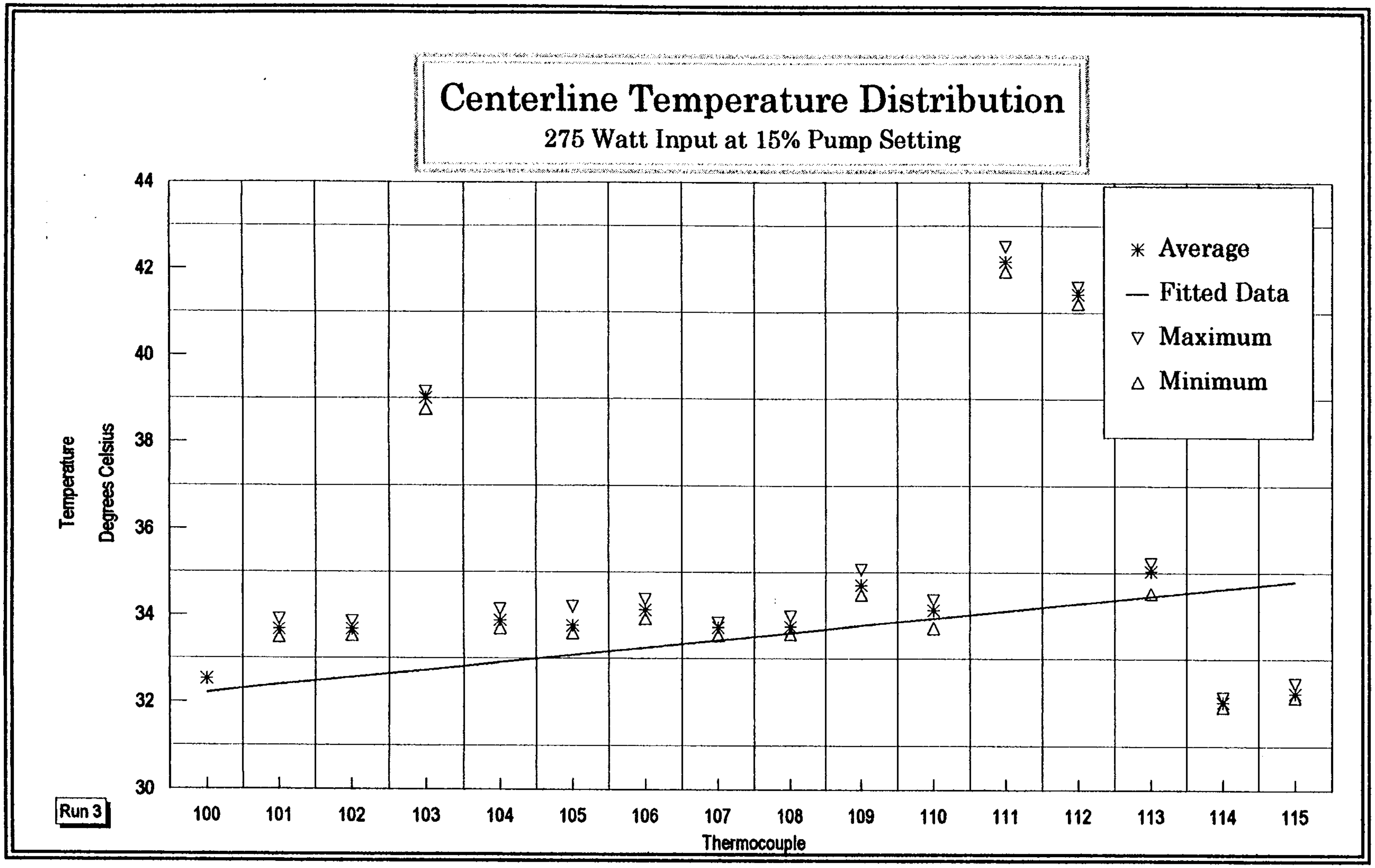


Figure 27. 275 Watts Heat Input at 15% Flow Rate

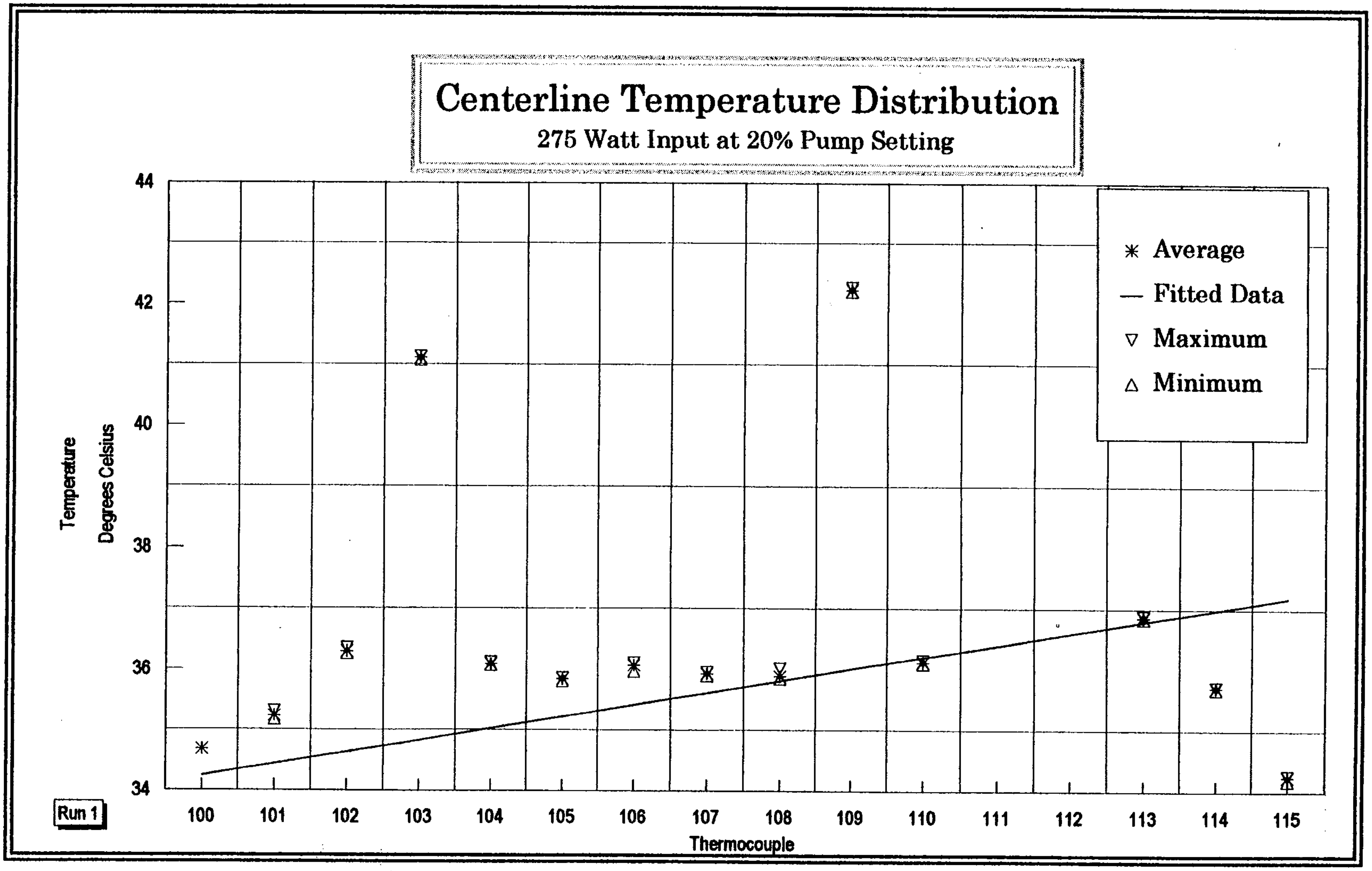


Figure 28. 275 Watts Heat Input at 20% Flow Rate

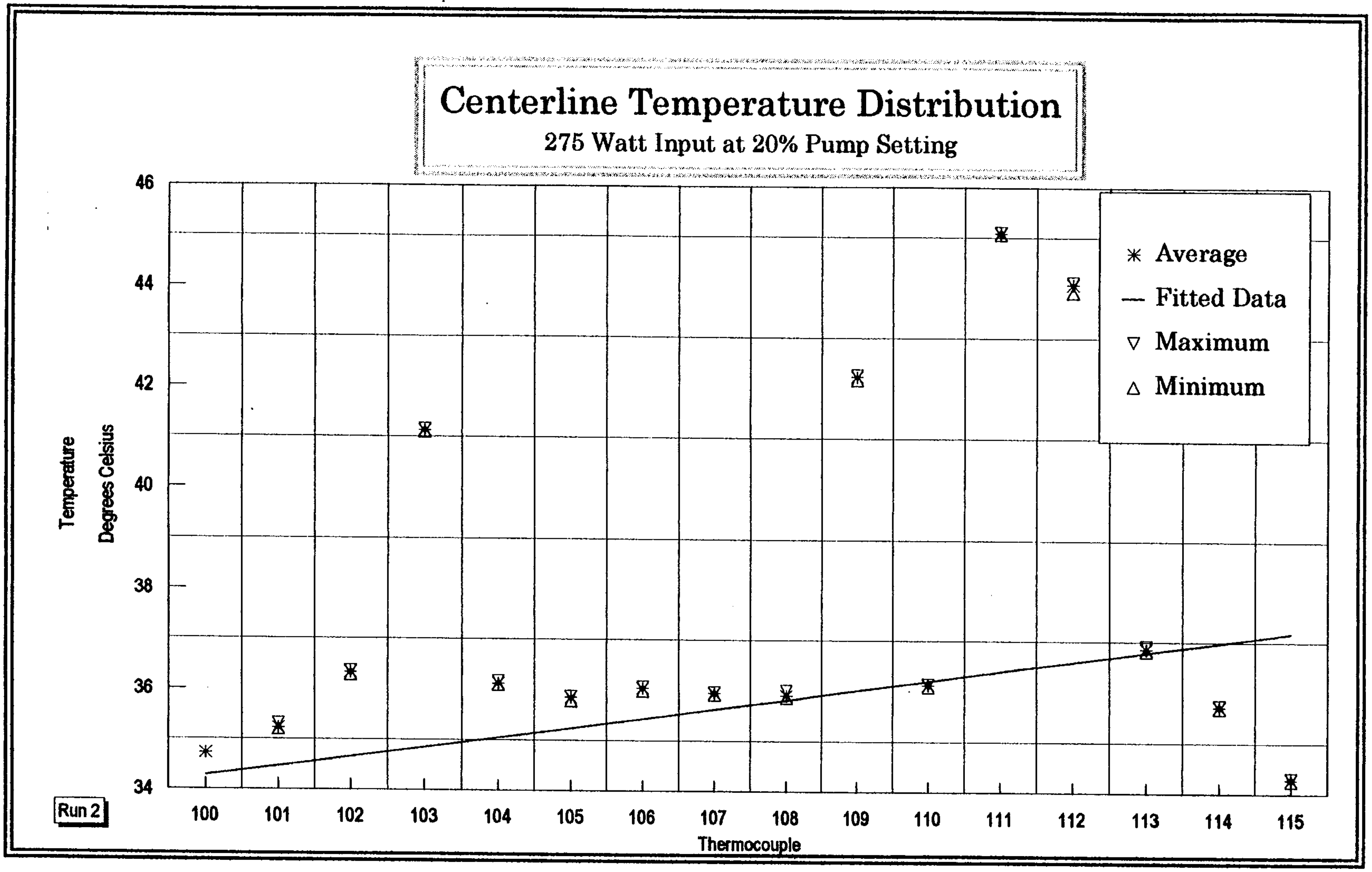


Figure 29. 275 Watts Heat Input at 20% Flow Rate

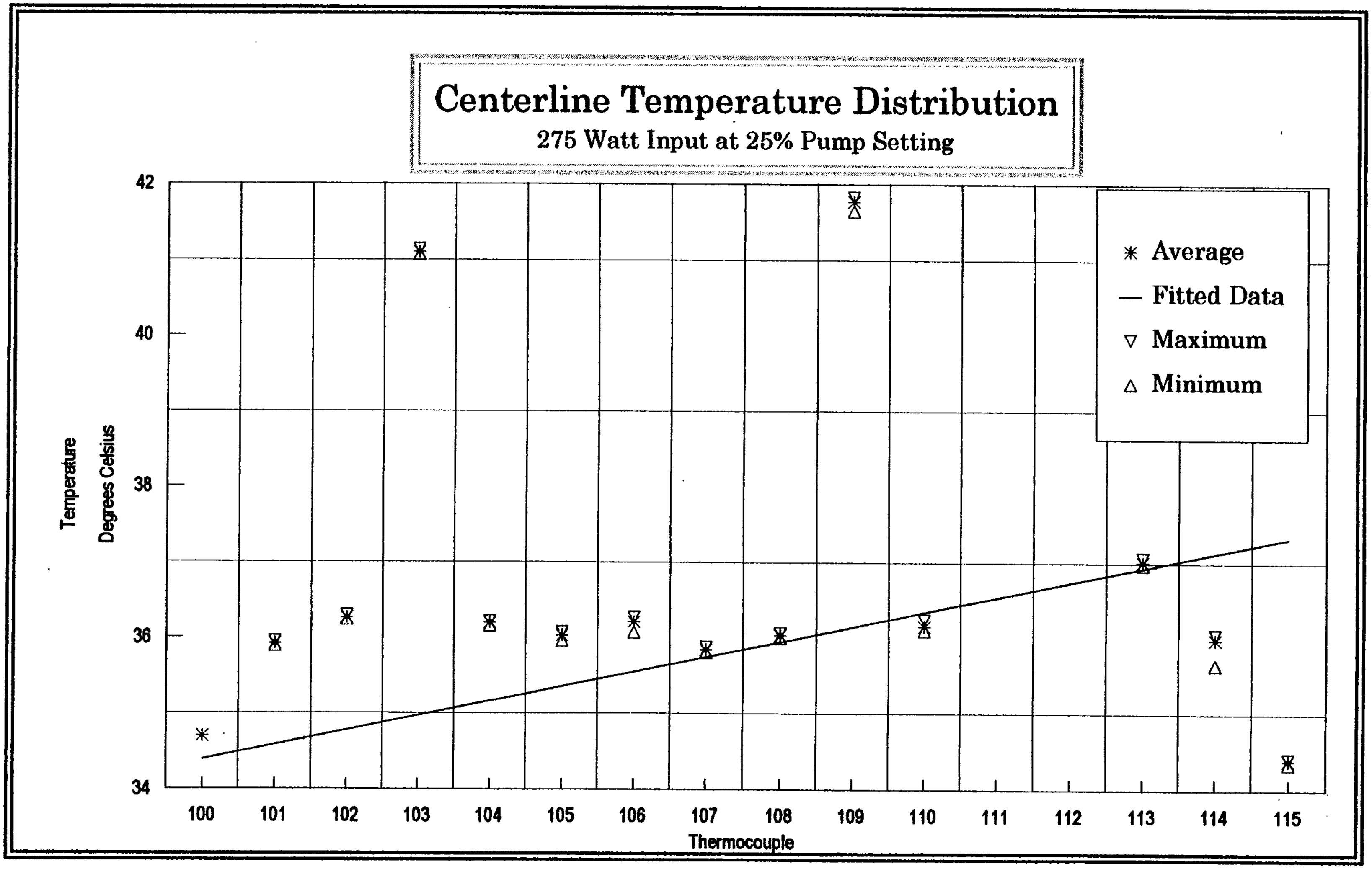


Figure 30. 275 Watts Heat Input at 25% Flow Rate

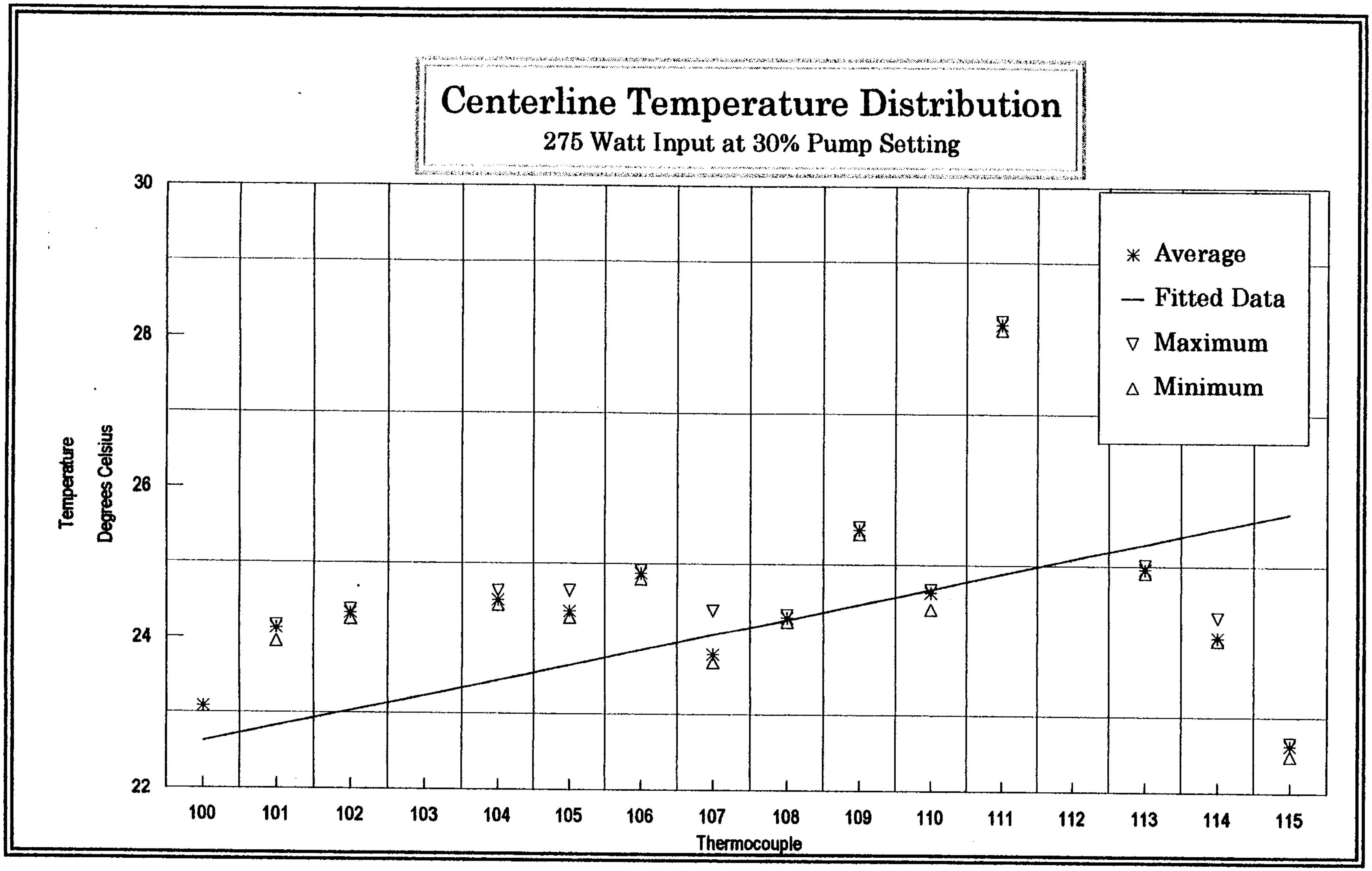


Figure 31. 275 Watts Heat Input at 30% Flow Rate

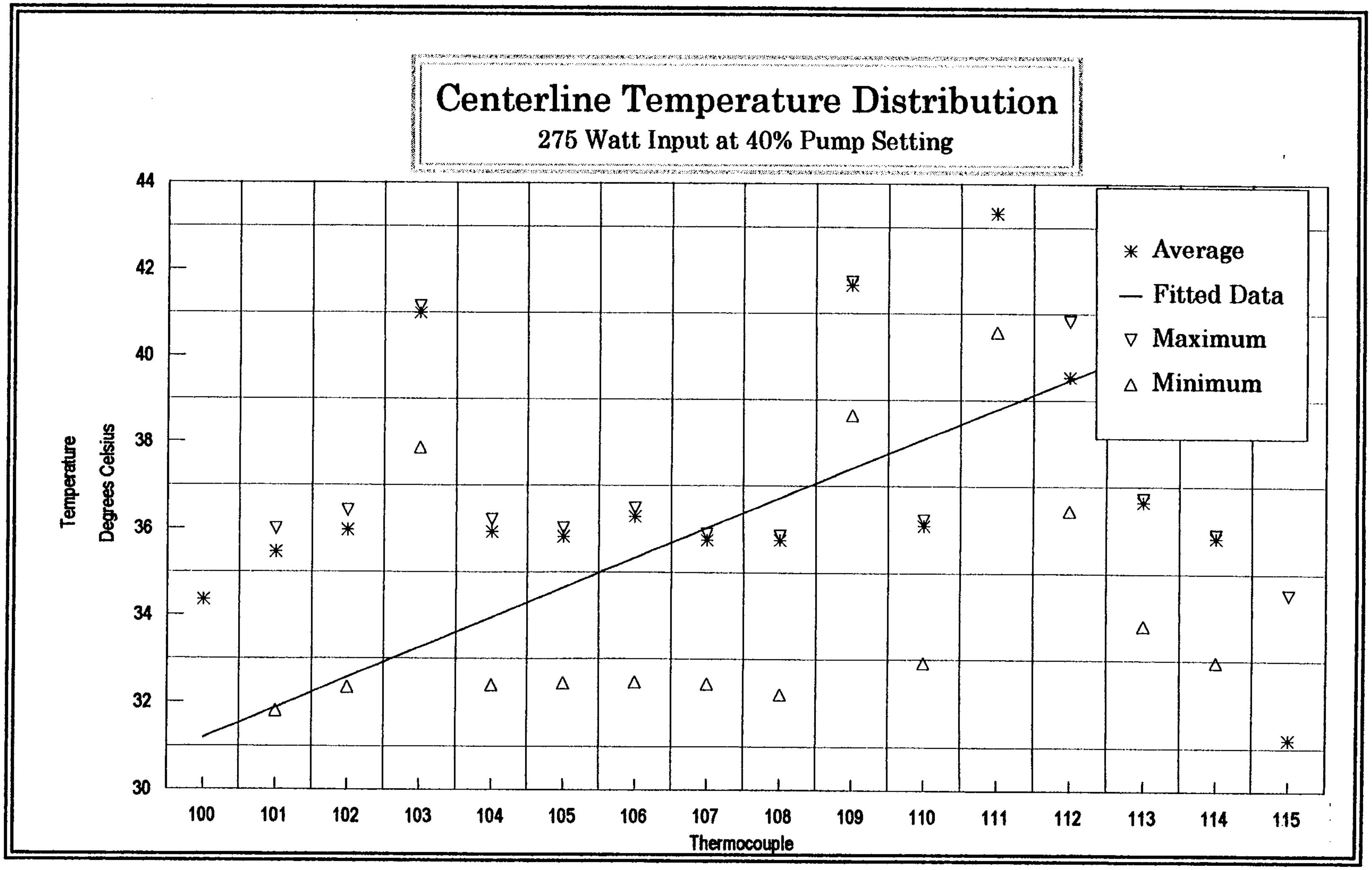


Figure 32. 275 Watts Heat Input at 40% Flow Rate

Thermocouple Data

Figures 33 through 53

Pump Setting	10				
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
100	22.189	22.297	21.950	0.1111	0.0123
101	20.045	20.116	20.007	0.0234	0.0005
102	22.908	23.045	22.727	0.1047	0.0110
103	29.819	29.963	29.688	0.0721	0.0052
104	23.653	23.811	23.486	0.0851	0.0072
105	24.636	24.957	24.387	0.1384	0.0192
106	24.360	24.558	24.031	0.1223	0.0149
107	23.440	23.636	22.796	0.2123	0.0451
108	22.969	23.272	22.572	0.2230	0.0497
109	29.629	29.822	29.567	0.0895	0.0080
110	23.543	23.611	23.426	0.0435	0.0019
111	30.997	31.083	30.921	0.0453	0.0021
112	29.919	30.001	29.872	0.0250	0.0006
113	24.272	24.330	24.180	0.0398	0.0016
114	22.921	23.021	22.785	0.0445	0.0020
115-Inlet Pipe	20.732	21.962	20.420	0.5620	0.3159
116 - Zero Reference	0.376	0.459	0.266	0.0410	0.0017
117 - Outlet Plenum	21.877	21.950	21.800	0.0336	0.0011
118 - Inlet Plenum	17.237	17.438	16.721	0.1787	0.0319
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
400	16.465	16.525	16.402	0.0274	0.0007
401	22.016	22.185	21.816	0.1085	0.0118
402	21.979	22.140	21.791	0.1070	0.0114
403	24.916	25.010	24.761	0.0692	0.0048
404	24.974	25.089	24.787	0.0866	0.0075
405	30.292	30.456	30.126	0.0927	0.0086
406	24.390	24.532	24.254	0.0783	0.0061
407	26.882	26.940	26.771	0.0458	0.0021
408	N/A	N/A	N/A	N/A	N/A
409	25.134	25.284	25.064	0.0498	0.0025
410	N/A	N/A	N/A	N/A	N/A
411	22.629	22.759	22.380	0.0542	0.0029
412	22.840	22.965	22.807	0.0303	0.0009

Figure 33. 100 Watts Heat Input at 10% Flow Rate

413	22.408	22.580	22.290	0.0605	0.0037
414 - Bath Temp	16.913	17.283	16.218	0.2711	0.0735
415 - Replaced 410	17.706	17.772	17.621	0.0349	0.0012
416 - Zero Reference	0.192	0.473	-0.196	0.1240	0.0154
417 - Top of Plate	22.260	22.315	22.186	0.0326	0.0011
418 - Ambient Air	21.471	21.703	21.213	0.1389	0.0193
419 - Bottom Insulation	28.469	28.603	27.926	0.1994	0.0398
421 - Side Insulation	15.815	16.082	15.589	0.1014	0.0103
422 - Plate Top (over 417)	16.879	16.905	16.852	0.0114	0.0001
423 - Side of Plate	19.660	19.718	19.612	0.0303	0.0009
V1 - Flow Meter VDC	0.554	0.571	0.547	0.0045	0.0000
V2 - Precision Resistor VDC	0.300	0.300	0.300	0.0000	0.0000
V3 - Heater Terminals Vdc	33.358	33.358	33.358	0.0001	0.0000
Bath Temp (F), (C)	22.000				
Sampling Time	0.162	0.179	0.155	0.0045	0.0000
Power (watts)	99.141	99.154	99.096	0.0152	0.0002
Flow Rate (mL/sec)	26.929	29.721	25.668		
	Plate Mean	Temperature			
Centerline Mean Temp	25.222				
Standard Deviation	3.262		Delta Temp	3.2224	
Variance	10.639				
Centerline Maximum Temp	30.997	31.083	30.921	0.2230	0.0497
Centerline Minimum Temp	20.045	20.116	20.007	0.0234	0.0005
Centerline Delta Temp	10.952	10.967	10.914	0.1996	0.0492

Figure 33. 100 Watts Heat Input at 10% Flow Rate

Pump Setting	10				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	23.150	23.191	23.117	0.0160	0.0003
101	24.348	24.377	24.322	0.0115	0.0001
102	24.497	24.565	24.470	0.0167	0.0003
103	30.520	30.561	30.479	0.0183	0.0003
104	24.741	24.889	24.679	0.0446	0.0020
105	22.919	22.979	22.857	0.0326	0.0011
106	25.335	25.356	25.304	0.0116	0.0001
107	24.796	24.819	24.771	0.0115	0.0001
108	24.745	24.775	24.657	0.0185	0.0003
109	25.962	26.008	25.929	0.0133	0.0002
110	25.254	25.279	25.231	0.0131	0.0002
111	28.670	28.698	28.633	0.0135	0.0002
112	31.666	31.688	31.639	0.0132	0.0002
113	25.669	25.745	25.637	0.0244	0.0006
114	24.751	24.791	24.721	0.0139	0.0002
115-Inlet Pipe	22.729	22.762	22.705	0.0127	0.0002
116 - Zero Reference	0.125	0.183	0.071	0.0251	0.0006
117 - Outlet Plenum	22.473	22.520	22.428	0.0188	0.0004
118 - Inlet Plenum	18.972	19.049	18.780	0.0565	0.0032
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	18.452	18.717	18.335	0.0739	0.0055
401	23.271	23.326	23.226	0.0218	0.0005
402	23.029	23.057	23.009	0.0101	0.0001
403	26.171	26.209	26.149	0.0103	0.0001
404	26.980	27.009	26.955	0.0107	0.0001
405	29.332	29.355	29.297	0.0121	0.0001
406	25.108	25.139	25.076	0.0114	0.0001
407	26.716	26.755	26.688	0.0128	0.0002
408	N/A	N/A	N/A	N/A	N/A
409	27.903	27.934	27.867	0.0134	0.0002
410	N/A	N/A	N/A	N/A	N/A
411	23.730	23.883	23.683	0.0295	0.0009
412	23.923	23.948	23.875	0.0137	0.0002

Figure 34. 150 Watts Heat Input at 0% Flow Rate

413	23.801	23.844	23.763	0.0159	0.0003
414 - Bath Temp	18.822	19.458	17.848	0.3641	0.1326
415 - Replaced 410	26.520	26.556	26.479	0.0157	0.0002
416 - Zero Reference	0.010	0.110	-0.165	0.0687	0.0047
417 - Top of Plate	23.466	23.559	23.381	0.0394	0.0016
418 - Ambient Air	16.773	16.848	16.714	0.0335	0.0011
419 - Bottom Insulation	29.959	29.985	29.934	0.0113	0.0001
421 - Side Insulation	18.678	18.876	18.493	0.1079	0.0116
422 - Plate Top (over 417)	16.739	16.810	16.646	0.0391	0.0015
423 - Side of Plate	21.812	22.054	21.553	0.1048	0.0110
V1 - Flow Meter Vdc	0.436	0.459	0.418	0.0107	0.0001
V2 - Precision Resistor Vdc	0.363	0.364	0.363	0.0003	0.0000
V3 - Heater Terminals Vdc	40.656	40.656	40.656	0.0001	0.0000
Bath Temp (C)	22.200				
Sampling Time	0.044	0.066	0.026	0.0107	0.0001
Power (watts)	146.158	146.466	145.938	0.1258	0.0158
Flow Rate (mL/sec)	7.272	11.041	4.259		
Plate Mean Temperature					
Centerline Mean Temp	25.991				
Standard Deviation	2.412		Delta Temp	3.7909	
Variance	5.816				
Centerline Maximum Temp	31.666	31.688	31.639	0.0446	0.0020
Centerline Minimum Temp	22.919	22.979	22.857	0.0115	0.0001
Centerline Delta Temp	8.746	8.710	8.781	0.0332	0.0019

Figure 34. 150 Watts Heat Input at 0% Flow Rate

Pump Setting	10				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	24.355	24.397	24.310	0.0187	0.0003
102	24.475	24.521	24.427	0.0191	0.0004
103	30.565	30.596	30.509	0.0177	0.0003
104	24.800	24.937	24.747	0.0388	0.0015
105	23.150	23.209	23.081	0.0284	0.0008
106	25.319	25.354	25.291	0.0137	0.0002
107	24.752	24.803	24.717	0.0141	0.0002
108	24.710	24.739	24.677	0.0140	0.0002
109	25.944	25.977	25.914	0.0146	0.0002
110	25.028	25.207	24.935	0.0624	0.0039
111	28.713	28.776	28.614	0.0307	0.0009
112	31.581	31.616	31.536	0.0166	0.0003
113	25.610	25.660	25.522	0.0345	0.0012
114	24.708	24.749	24.674	0.0139	0.0002
115-Inlet Pipe	22.759	22.825	22.701	0.0240	0.0006
116 - Zero Reference	0.159	0.241	0.077	0.0291	0.0008
117 - Outlet Plenum	22.517	22.565	22.449	0.0292	0.0009
118 - Inlet Plenum	19.167	19.527	18.188	0.2969	0.0882
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	18.676	18.829	18.556	0.0638	0.0041
401	23.219	23.246	23.188	0.0103	0.0001
402	23.007	23.030	22.988	0.0102	0.0001
403	26.230	26.267	26.187	0.0187	0.0004
404	26.976	27.016	26.944	0.0155	0.0002
405	29.362	29.433	29.290	0.0241	0.0006
406	25.073	25.108	25.008	0.0174	0.0003
407	26.649	26.688	26.616	0.0130	0.0002
408	N/A	N/A	N/A	N/A	N/A
409	27.862	27.896	27.835	0.0108	0.0001
410	N/A	N/A	N/A	N/A	N/A
411	23.677	23.702	23.645	0.0120	0.0001
412	23.874	23.913	23.823	0.0122	0.0001

Figure 35. 150 Watts Heat Input at 10% Flow Rate

413	23.760	23.803	23.698	0.0159	0.0003
414 - Bath Temp	18.775	19.434	17.622	0.4124	0.1701
415 - Replaced 410	26.520	26.610	26.432	0.0443	0.0020
416 - Zero Reference	0.061	0.274	-0.101	0.0549	0.0030
417 - Top of Plate	23.377	23.478	23.321	0.0307	0.0009
418 - Ambient Air	16.990	17.088	16.927	0.0464	0.0022
419 - Bottom Insulation	29.973	30.002	29.919	0.0190	0.0004
421 - Side Insulation	18.527	18.750	18.330	0.1009	0.0102
422 - Plate Top (over 417)	17.168	17.254	17.086	0.0500	0.0025
423 - Side of Plate	22.006	22.178	21.748	0.1086	0.0118
V1 - Flow Meter Vdc	0.558	0.567	0.550	0.0039	0.0000
V2 - Precision Resistor Vdc	0.364	0.364	0.363	0.0004	0.0000
V3 - Heater Terminals Vdc	40.657	40.657	40.657	0.0001	0.0000
Bath Temp (C)	22.100				
Sampling Time	0.166	0.175	0.158	0.0039	0.0000
Power (watts)	146.353	146.589	145.951	0.1512	0.0229
Flow Rate (mL/sec)	27.604	29.099	26.290		
	Plate Mean	Temperature			
Centerline Mean Temp	25.979				
Standard Deviation	2.396		Delta Temp	3.8793	
Variance	5.742				
Centerline Maximum Temp	31.581	31.616	31.536	0.0624	0.0039
Centerline Minimum Temp	23.150	23.209	23.081	0.0137	0.0002
Centerline Delta Temp	8.432	8.407	8.455	0.0487	0.0037

Figure 35. 150 Watts Heat Input at 10% Flow Rate

Pump Setting	20				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	23.150	23.191	23.117	0.0160	0.0003
101	24.348	24.377	24.322	0.0115	0.0001
102	24.497	24.565	24.470	0.0167	0.0003
103	30.520	30.561	30.479	0.0183	0.0003
104	24.741	24.889	24.679	0.0446	0.0020
105	22.919	22.979	22.857	0.0326	0.0011
106	25.335	25.356	25.304	0.0116	0.0001
107	24.796	24.819	24.771	0.0115	0.0001
108	24.745	24.775	24.657	0.0185	0.0003
109	25.962	26.008	25.929	0.0133	0.0002
110	25.254	25.279	25.231	0.0131	0.0002
111	28.670	28.698	28.633	0.0135	0.0002
112	31.666	31.688	31.639	0.0132	0.0002
113	25.669	25.745	25.637	0.0244	0.0006
114	24.751	24.791	24.721	0.0139	0.0002
115-Inlet Pipe	22.729	22.762	22.705	0.0127	0.0002
116 - Zero Reference	0.125	0.183	0.071	0.0251	0.0006
117 - Outlet Plenum	22.473	22.520	22.428	0.0188	0.0004
118 - Inlet Plenum	18.972	19.049	18.780	0.0565	0.0032
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	18.452	18.717	18.335	0.0739	0.0055
401	23.271	23.326	23.226	0.0218	0.0005
402	23.029	23.057	23.009	0.0101	0.0001
403	26.171	26.209	26.149	0.0103	0.0001
404	26.980	27.009	26.955	0.0107	0.0001
405	29.332	29.355	29.297	0.0121	0.0001
406	25.108	25.139	25.076	0.0114	0.0001
407	26.716	26.755	26.688	0.0128	0.0002
408	N/A	N/A	N/A	N/A	N/A
409	27.903	27.934	27.867	0.0134	0.0002
410	N/A	N/A	N/A	N/A	N/A
411	23.730	23.883	23.683	0.0295	0.0009
412	23.923	23.948	23.875	0.0137	0.0002

Figure 36. 150 Watts Heat Input at 20% Flow Rate

413	23.801	23.844	23.763	0.0159	0.0003
414 - Bath Temp	18.822	19.458	17.848	0.3641	0.1326
415 - Replaced 410	26.520	26.556	26.479	0.0157	0.0002
416 - Zero Reference	0.010	0.110	-0.165	0.0687	0.0047
417 - Top of Plate	23.466	23.559	23.381	0.0394	0.0016
418 - Ambient Air	16.773	16.848	16.714	0.0335	0.0011
419 - Bottom Insulation	29.959	29.985	29.934	0.0113	0.0001
421 - Side Insulation	18.678	18.876	18.493	0.1079	0.0116
422 - Plate Top (over 417)	16.739	16.810	16.646	0.0391	0.0015
423 - Side of Plate	21.812	22.054	21.553	0.1048	0.0110
V1 - Flow Meter Vdc	0.436	0.459	0.418	0.0107	0.0001
V2 - Precision Resistor Vdc	0.363	0.364	0.363	0.0003	0.0000
V3 - Heater Terminals Vdc	40.656	40.656	40.656	0.0001	0.0000
Bath Temp (C)	22.100				
Sampling Time	0.044	0.066	0.026	0.0107	0.0001
Power (watts)	146.158	146.466	145.938	0.1258	0.0158
Flow Rate (mL/sec)	7.271677	11.041	4.25906		
	Plate Mean	Temperature			
Centerline Mean Temp	25.991				
Standard Deviation	2.412		Delta Temp	3.8909	
Variance	5.816				
Centerline Maximum Temp	31.66576	31.68848	31.63867	0.0446	0.0020
Centerline Minimum Temp	22.72873	22.76172	22.70508	0.0115	0.0001
Centerline Delta Temp	8.937034	8.92676	8.93359	0.0331	0.0019

Figure 36. 150 Watts Heat Input at 20% Flow Rate

Pump Setting	0				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	33.291	33.850	33.224	0.0741	0.0055
102	32.980	33.084	32.644	0.0572	0.0033
103	37.292	37.349	37.126	0.0349	0.0012
104	33.521	33.606	33.439	0.0340	0.0012
105	32.899	32.995	32.784	0.0335	0.0011
106	33.745	33.830	33.679	0.0310	0.0010
107	33.320	33.452	33.252	0.0335	0.0011
108	33.482	33.635	33.379	0.0450	0.0020
109	34.098	34.193	33.950	0.0361	0.0013
110	33.677	33.750	33.525	0.0385	0.0015
111	40.537	40.604	40.351	0.0376	0.0014
112	39.887	39.962	39.807	0.0328	0.0011
113	34.421	36.041	34.278	0.2163	0.0468
114	31.718	31.873	31.398	0.0573	0.0033
115-Inlet Pipe	31.821	31.978	31.694	0.0513	0.0026
116 - Zero Reference	-0.068	0.125	-0.159	0.0465	0.0022
117 - Outlet Plenum	32.132	32.182	32.068	0.0202	0.0004
118 - Inlet Plenum	18.761	19.359	17.330	0.3906	0.1525
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.457	19.622	19.366	0.0509	0.0026
401	32.461	32.604	32.376	0.0429	0.0018
402	32.092	32.132	32.060	0.0142	0.0002
403	33.817	33.921	33.740	0.0292	0.0009
404	34.608	34.699	34.465	0.0345	0.0012
405	35.772	35.874	35.661	0.0472	0.0022
406	33.341	33.471	33.240	0.0415	0.0017
407	34.521	34.684	34.419	0.0418	0.0018
408	N/A	N/A	N/A	N/A	N/A
409	34.641	34.709	34.530	0.0324	0.0011
410	N/A	N/A	N/A	N/A	N/A
411	32.403	32.507	32.252	0.0535	0.0029
412	32.378	32.445	32.296	0.0358	0.0013

Figure 37. 210 Watts Heat Input at 0% Flow Rate

413	32.415	32.466	32.348	0.0316	0.0010
414 - Bath Temp	19.711	20.490	18.434	0.4190	0.1756
415 - Replaced 410	35.696	35.935	35.486	0.1308	0.0171
416 - Zero Reference	-0.019	0.407	-0.301	0.1035	0.0107
417 - Top of Plate	32.441	32.550	32.296	0.0474	0.0022
418 - Ambient Air	16.976	17.066	16.850	0.0421	0.0018
419 - Bottom Insulation	35.156	35.264	35.013	0.0489	0.0024
	N/A	N/A	N/A	N/A	N/A
421 - Side Insulation	18.686	18.786	18.629	0.0309	0.0010
422 - Plate Top (over 417)	18.142	18.239	18.063	0.0412	0.0017
423 - Side of Plate	29.625	29.773	29.496	0.0654	0.0043
V1 - Flow Meter Vdc	0.392	0.403	0.391	0.0015	0.0000
V2 - Precision Resistor Vdc	31.853	31.853	31.853	0.0001	0.0000
V3 - Heater Terminals Vdc	68.077	68.077	68.076	0.0002	0.0000
Bath Temp (C)	32.2				
Sampling Time	0.000	0.011	0.000	0.0014	0.0000
Power (watts)	210.529	210.531	210.526	0.0011	0.0000
Flow Rate (mL/sec)	-0.08185	1.828539	-0.13887		
	Plate Mean	Temperature			
Centerline Mean Temp	34.633				
Standard Deviation	2.562		Delta Temp	2.4335	
Variance	6.563				
Centerline Maximum Temp	40.537	40.604	40.351	0.2163	0.0468
Centerline Minimum Temp	31.718	31.873	31.398	0.0310	0.0010
Centerline Delta Temp	8.819	8.731	8.952	0.1853	0.0458

Figure 37. 210 Watts Heat Input at 0% Flow Rate

Pump Setting	15		Run One		
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
100	N/A	N/A	N/A	N/A	N/A
101	30.422	30.773	29.979	0.2158	0.0466
102	33.061	33.125	33.000	0.0242	0.0006
103	36.486	37.887	36.014	0.6340	0.4019
104	33.366	33.501	33.133	0.0779	0.0061
105	32.888	32.989	32.737	0.0422	0.0018
106	33.509	33.716	32.813	0.1810	0.0328
107	33.480	33.629	33.324	0.0946	0.0089
108	33.496	33.622	33.419	0.0482	0.0023
109	34.198	34.310	34.092	0.0559	0.0031
110	33.555	33.733	33.436	0.0775	0.0060
111	39.833	40.063	39.748	0.0763	0.0058
112	35.831	36.691	35.667	0.2411	0.0581
113	34.137	34.200	34.053	0.0383	0.0015
114	33.221	33.329	33.167	0.0290	0.0008
115-Inlet Pipe	32.240	32.287	32.201	0.0196	0.0004
116 - Zero Reference	0.026	0.047	0.005	0.0089	0.0001
117 - Outlet Plenum	32.256	32.295	32.209	0.0238	0.0006
118 - Inlet Plenum	18.961	19.945	17.523	0.5167	0.2670
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
400	32.324	32.351	32.303	0.0114	0.0001
401	32.877	32.943	32.673	0.0424	0.0018
402	32.324	32.359	32.257	0.0235	0.0006
403	34.032	34.307	33.936	0.0880	0.0078
404	34.842	35.059	34.739	0.0960	0.0092
405	37.046	37.171	36.971	0.0530	0.0028
406	34.023	34.091	33.957	0.0373	0.0014
407	35.017	35.240	34.674	0.1402	0.0196
408	N/A	N/A	N/A	N/A	N/A
409	35.144	35.261	35.047	0.0580	0.0034
410	N/A	N/A	N/A	N/A	N/A
411	32.615	32.644	32.587	0.0160	0.0003
412	32.535	32.569	32.493	0.0219	0.0005

Figure 38. 210 Watts Heat Input at 15% Flow Rate

413	32.588	32.625	32.540	0.0222	0.0005
414 - Bath Temp	19.597	20.279	18.966	0.2929	0.0858
415 - Replaced 410	35.802	36.018	35.712	0.0677	0.0046
416 - Zero Reference	0.073	0.209	-0.108	0.0761	0.0058
417 - Top of Plate	32.403	32.647	32.249	0.0930	0.0087
418 - Ambient Air	17.341	17.448	17.275	0.0492	0.0024
419 - Bottom Insulation	33.499	35.630	32.068	0.8786	0.7720
421 - Side Insulation	18.927	19.046	18.815	0.0726	0.0053
422 - Plate Top (over 417)	16.959	17.008	16.914	0.0216	0.0005
423 - Side of Plate	25.322	25.813	25.103	0.1683	0.0283
V1 - Flow Meter Vdc	0.539	0.569	0.490	0.0326	0.0011
V2 - Precision Resistor Vdc	31.853	31.854	31.852	0.0004	0.0000
V3 - Heater Terminals Vdc	68.084	68.084	68.084	0.0001	0.0000
Bath Temp (C)	32.2				
Sampling Time	0.147	0.177	0.098	0.0326	0.0011
Power (watts)	214.723	214.727	214.717	0.0026	0.0000
Flow Rate (mL/sec)	24.423	29.377	16.204		
	Plate Mean	Temperature			
Centerline Mean Temp	34.106				
Standard Deviation	2.076		Delta Temp	1.9060	
Variance	4.311				
Centerline Maximum Temp	39.833	40.063	39.748	0.6340	0.4019
Centerline Minimum Temp	30.422	30.773	29.979	0.0242	0.0006
Centerline Delta Temp	9.412	9.289	9.769	0.6098	0.4013

Figure 38. 210 Watts Heat Input at 15% Flow Rate

Pump Setting	15		Run Two		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	31.791	33.015	30.069	1.1683	1.3649
102	33.143	33.207	33.084	0.0245	0.0006
103	36.298	36.834	36.108	0.1880	0.0353
104	33.414	33.455	33.257	0.0264	0.0007
105	32.937	33.094	32.476	0.0857	0.0073
106	33.435	33.655	33.158	0.1185	0.0140
107	33.530	33.650	33.413	0.0447	0.0020
108	33.576	33.624	33.497	0.0196	0.0004
109	34.298	34.350	34.226	0.0261	0.0007
110	33.726	33.850	33.574	0.0732	0.0054
111	39.786	39.873	39.751	0.0214	0.0005
112	35.164	35.284	35.109	0.0305	0.0009
113	34.393	34.471	34.296	0.0328	0.0011
114	33.431	33.659	33.321	0.0858	0.0074
115-Inlet Pipe	32.323	32.363	32.237	0.0209	0.0004
116 - Zero Reference	0.125	0.194	-0.213	0.0527	0.0028
117 - Outlet Plenum	32.316	32.408	32.261	0.0288	0.0008
118 - Inlet Plenum	18.917	20.193	17.357	0.6689	0.4474
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	22.125	32.553	18.891	5.4980	30.2276
401	33.029	33.684	32.736	0.2420	0.0586
402	32.377	32.419	32.324	0.0225	0.0005
403	34.033	34.079	33.975	0.0193	0.0004
404	34.846	34.920	34.750	0.0421	0.0018
405	36.468	36.929	35.859	0.3648	0.1330
406	34.004	34.076	33.913	0.0409	0.0017
407	34.972	35.152	34.732	0.0854	0.0073
408	N/A	N/A	N/A	N/A	N/A
409	34.761	34.908	34.571	0.0784	0.0062
410	N/A	N/A	N/A	N/A	N/A
411	32.654	32.761	32.531	0.0289	0.0008
412	32.556	32.590	32.437	0.0187	0.0004

Figure 39. 210 Watts Heat Input at 15% Flow Rate

413	32.597	32.640	32.549	0.0143	0.0002
414 - Bath Temp	20.092	20.649	19.342	0.2973	0.0884
415 - Replaced 410	35.798	36.080	35.439	0.1163	0.0135
416 - Zero Reference	0.105	0.356	-0.176	0.1090	0.0119
417 - Top of Plate	32.423	32.630	32.341	0.0461	0.0021
418 - Ambient Air	19.576	31.989	17.184	5.1134	26.1465
419 - Bottom Insulation	32.758	32.981	32.459	0.1094	0.0120
421 - Side Insulation	20.069	20.631	19.166	0.4539	0.2061
422 - Plate Top (over 417)	17.863	18.384	17.312	0.3611	0.1304
423 - Side of Plate	26.141	26.616	25.646	0.2219	0.0493
V1 - Flow Meter Vdc	0.520	0.548	0.490	0.0142	0.0002
V2 - Precision Resistor Vdc	31.854	31.856	31.850	0.0011	0.0000
V3 - Heater Terminals Vdc	68.084	68.085	68.084	0.0001	0.0000
Bath Temp (C)	32.8				
Sampling Time	0.128	0.156	0.098	0.0142	0.0002
Power (watts)	210.560	210.570	210.535	0.0071	0.0000
Flow Rate (mL/sec)	21.30649	25.92346	16.3037		
	Plate Mean	Temperature			
Centerline Mean Temp	34.209				
Standard Deviation	1.851		Delta Temp	1.4087	
Variance	3.425				
Centerline Maximum Temp	39.786	39.873	39.751	1.1683	1.3649
Centerline Minimum Temp	31.791	33.015	30.069	0.0196	0.0004
Centerline Delta Temp	7.995	6.858	9.682	1.1487	1.3645

Figure 39. 210 Watts Heat Input at 15% Flow Rate

Pump Setting	15		Run Three		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	33.560	33.614	33.484	0.0243	0.0005
102	33.159	33.228	32.962	0.0359	0.0013
103	38.867	39.179	38.777	0.0475	0.0023
104	33.496	33.546	33.414	0.0227	0.0005
105	33.105	33.189	32.980	0.0308	0.0010
106	33.614	34.020	33.203	0.1050	0.0110
107	33.533	33.660	33.292	0.0471	0.0022
108	33.692	33.734	33.519	0.0295	0.0009
109	34.210	34.467	34.056	0.0459	0.0021
110	33.750	33.867	33.651	0.0315	0.0010
111	40.616	40.695	40.235	0.0546	0.0030
112	39.886	39.998	39.829	0.0264	0.0007
113	34.406	34.689	34.328	0.0448	0.0020
114	31.981	32.031	31.827	0.0357	0.0013
115-Inlet Pipe	32.291	32.347	32.162	0.0284	0.0008
116 - Zero Reference	0.129	0.172	0.079	0.0179	0.0003
117 - Outlet Plenum	32.336	32.390	32.298	0.0176	0.0003
118 - Inlet Plenum	19.472	19.831	18.660	0.2611	0.0682
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.112	19.483	18.958	0.1233	0.0152
401	33.069	33.155	32.910	0.0393	0.0015
402	32.424	32.456	32.255	0.0268	0.0007
403	34.405	35.140	34.330	0.0970	0.0094
404	35.033	35.176	34.903	0.0330	0.0011
405	37.055	37.134	36.999	0.0265	0.0007
406	34.047	34.101	33.257	0.1046	0.0109
407	34.930	35.014	34.874	0.0215	0.0005
408	N/A	N/A	N/A	N/A	N/A
409	35.215	35.277	35.143	0.0245	0.0006
410	N/A	N/A	N/A	N/A	N/A
411	32.432	32.595	32.364	0.0386	0.0015
412	32.515	32.564	32.450	0.0242	0.0006

Figure 40. 210 Watts Heat Input at 15% Flow Rate

413	32.546	32.585	32.491	0.0203	0.0004
414 - Bath Temp	20.640	21.119	19.927	0.2901	0.0842
415 - Replaced 410	35.763	35.837	35.630	0.0415	0.0017
416 - Zero Reference	0.156	0.269	-0.111	0.0826	0.0068
417 - Top of Plate	32.479	32.614	32.256	0.0426	0.0018
418 - Ambient Air	17.277	17.328	17.238	0.0206	0.0004
419 - Bottom Insulation	37.210	37.279	37.116	0.0235	0.0006
421 - Side Insulation	18.541	18.604	18.463	0.0300	0.0009
422 - Plate Top (over 417)	18.318	18.516	18.245	0.0427	0.0018
423 - Side of Plate	29.124	29.409	28.938	0.0871	0.0076
V1 - Flow Meter Vdc	0.527	0.543	0.511	0.0063	0.0000
V2 - Precision Resistor Vdc	31.855	31.855	31.853	0.0007	0.0000
V3 - Heater Terminals Vdc	68.085	68.085	68.084	0.0001	0.0000
Bath Temp (C)	32.8				
Sampling Time	0.135	0.151	0.119	0.0063	0.0000
Power (watts)	210.564	210.569	210.555	0.0045	0.0000
Flow Rate (mL/sec)	22.34715	25.10121	19.74101		
	Plate Mean	Temperature			
Centerline Mean Temp	34.848				
Standard Deviation	2.656		Delta Temp	2.0482	
Variance	7.057				
Centerline Maximum Temp	40.616	40.695	40.235	0.1050	0.0110
Centerline Minimum Temp	31.981	32.031	31.827	0.0227	0.0005
Centerline Delta Temp	8.635	8.664	8.408	0.0823	0.0105

Figure 40. 210 Watts Heat Input at 15% Flow Rate

Pump Setting					
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	33.635	33.678	33.596	0.0195	0.0004
102	33.563	33.603	33.508	0.0196	0.0004
103	38.163	38.240	38.113	0.0291	0.0008
104	33.569	33.608	33.530	0.0161	0.0003
105	33.093	33.241	32.992	0.0354	0.0012
106	33.913	34.026	33.534	0.1161	0.0135
107	33.583	33.729	32.649	0.1410	0.0199
108	33.676	33.742	33.593	0.0341	0.0012
109	34.269	34.325	34.180	0.0283	0.0008
110	33.814	33.864	33.543	0.0392	0.0015
111	40.610	40.728	40.563	0.0281	0.0008
112	39.828	39.890	39.789	0.0208	0.0004
113	34.412	34.510	34.346	0.0284	0.0008
114	31.963	32.038	31.898	0.0269	0.0007
115-Inlet Pipe	32.297	32.350	32.214	0.0236	0.0006
116 - Zero Reference	0.097	0.127	0.074	0.0128	0.0002
117 - Outlet Plenum	32.241	32.278	32.192	0.0165	0.0003
118 - Inlet Plenum	18.879	19.694	18.099	0.4064	0.1652
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.573	19.607	19.526	0.0177	0.0003
401	33.022	33.064	32.892	0.0277	0.0008
402	32.450	32.486	32.415	0.0155	0.0002
403	33.539	33.617	33.478	0.0320	0.0010
404	35.019	35.066	34.970	0.0205	0.0004
405	37.085	37.149	37.016	0.0208	0.0004
406	33.684	33.879	33.233	0.1848	0.0342
407	34.848	35.005	34.736	0.0769	0.0059
408	N/A	N/A	N/A	N/A	N/A
409	35.200	35.254	35.140	0.0258	0.0007
410	N/A	N/A	N/A	N/A	N/A
411	32.637	32.675	32.466	0.0330	0.0011
412	32.573	32.623	32.544	0.0148	0.0002

Figure 41. 210 Watts Heat Input at 20% Flow Rate

413	32.595	32.617	32.562	0.0126	0.0002
414 - Bath Temp	20.436	21.208	19.278	0.3483	0.1213
415 - Replaced 410	35.925	36.013	35.865	0.0276	0.0008
416 - Zero Reference	0.061	0.225	-0.179	0.0823	0.0068
417 - Top of Plate	32.357	32.424	32.277	0.0291	0.0008
418 - Ambient Air	17.324	17.412	17.228	0.0467	0.0022
419 - Bottom Insulation	37.087	37.208	37.039	0.0343	0.0012
421 - Side Insulation	18.620	18.719	18.530	0.0494	0.0024
422 - Plate Top (over 417)	18.857	18.962	18.306	0.0766	0.0059
423 - Side of Plate	29.609	30.295	29.120	0.4297	0.1846
V1 - Flow Meter Vdc	0.528	0.546	0.520	0.0053	0.0000
V2 - Precision Resistor Vdc	31.855	31.855	31.854	0.0002	0.0000
V3 - Heater Terminals Vdc	68.084	68.084	68.084	0.0001	0.0000
Bath Temp (C)	22.1				
Sampling Time	N/A				
Power (watts)	210.563	210.566	210.559	0.0014	0.0000
Flow Rate (mL/sec)	22.56937	25.60486	21.15394		
	Plate Mean	Temperature			
Centerline Mean Temp	34.864				
Standard Deviation	2.544		Delta Temp	12.7636	
Variance	6.471				
Centerline Maximum Temp	40.610	40.728	40.563	0.1410	0.0199
Centerline Minimum Temp	31.963	32.038	31.898	0.0161	0.0003
Centerline Delta Temp	8.647	8.689	8.665	0.1249	0.0196

Figure 41. 210 Watts Heat Input at 20% Flow Rate

Pump Setting	25				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	33.563	33.644	33.374	0.0448	0.0020
102	33.531	33.762	33.429	0.0416	0.0017
103	38.101	38.165	37.956	0.0525	0.0028
104	33.705	33.811	33.411	0.0979	0.0096
105	33.517	33.693	33.245	0.1314	0.0173
106	33.717	33.941	33.342	0.1471	0.0216
107	33.373	33.497	33.298	0.0371	0.0014
108	33.576	33.645	33.490	0.0348	0.0012
109	34.241	34.310	34.194	0.0245	0.0006
110	33.783	33.819	33.736	0.0190	0.0004
111	40.548	40.629	40.485	0.0255	0.0006
112	39.777	39.903	39.722	0.0264	0.0007
113	34.445	34.518	34.351	0.0273	0.0007
114	31.890	31.941	31.818	0.0285	0.0008
115-Inlet Pipe	32.194	32.276	32.001	0.0668	0.0045
116 - Zero Reference	-0.027	0.013	-0.061	0.0163	0.0003
117 - Outlet Plenum	32.060	32.179	31.449	0.1406	0.0198
118 - Inlet Plenum	18.567	19.432	17.688	0.3144	0.0989
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.840	19.939	19.776	0.0356	0.0013
401	32.910	33.258	32.804	0.0672	0.0045
402	32.448	32.506	32.340	0.0415	0.0017
403	33.589	33.625	33.541	0.0181	0.0003
404	34.918	34.995	34.797	0.0381	0.0014
405	35.616	35.733	35.384	0.1094	0.0120
406	33.428	33.590	32.835	0.2448	0.0599
407	34.587	34.666	34.468	0.0441	0.0019
408	N/A	N/A	N/A	N/A	N/A
409	34.965	35.065	34.820	0.0805	0.0065
410	N/A	N/A	N/A	N/A	N/A
411	32.574	32.707	32.398	0.0682	0.0047
412	32.544	32.565	32.522	0.0113	0.0001

Figure 42. 210 Watts Heat Input at 25% Flow Rate

413	32.576	32.605	32.534	0.0150	0.0002
414 - Bath Temp	19.711	20.578	18.468	0.4241	0.1798
415 - Replaced 410	35.783	35.985	35.668	0.0734	0.0054
416 - Zero Reference	0.022	0.187	-0.231	0.0896	0.0080
417 - Top of Plate	32.279	32.386	32.172	0.0411	0.0017
418 - Ambient Air	17.106	17.228	16.998	0.0474	0.0022
419 - Bottom Insulation	36.407	36.712	36.004	0.2245	0.0504
	N/A	N/A	N/A	N/A	N/A
421 - Side Insulation	18.326	18.592	18.166	0.1148	0.0132
422 - Plate Top (over 417)	19.087	19.185	18.986	0.0312	0.0010
423 - Side of Plate	30.313	30.503	30.166	0.0741	0.0055
V1 - Flow Meter Vdc	0.541	0.562	0.526	0.0073	0.0001
V2 - Precision Resistor Vdc	31.855	31.855	31.854	0.0001	0.0000
V3 - Heater Terminals Vdc	68.081	68.082	68.081	0.0003	0.0000
Bath Temp (C)	32.2				
Sampling Time	N/A				
Power (watts)	210.554	210.556	210.551	0.0012	0.0000
Flow Rate (mL/sec)	24.6594	28.14285	22.27718		
	Plate Mean	Temperature			
Centerline Mean Temp	34.840				
Standard Deviation	2.526		Delta Temp	2.6405	
Variance	6.379				
Centerline Maximum Temp	40.548	40.629	40.485	0.1471	0.0216
Centerline Minimum Temp	31.890	31.941	31.818	0.0190	0.0004
Centerline Delta Temp	8.658	8.688	8.667	0.1282	0.0213

Figure 42. 210 Watts Heat Input at 25% Flow Rate

Pump Setting	15				
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
100	32.52824	33.05665	32.41553	0.080657	0.009587
101	33.6794	33.91211	33.49707	0.062601	0.003919
102	33.67123	33.8584	33.52734	0.05738	0.003292
103	39.01044	39.14551	38.75293	0.05486	0.00301
104	33.8882	34.1377	33.69629	0.055788	0.003112
105	33.77191	34.20215	33.58691	0.082866	0.006867
106	34.138	34.37012	33.9209	0.065734	0.004321
107	33.72125	33.83203	33.54199	0.048287	0.002332
108	33.74936	33.97852	33.56348	0.068509	0.004693
109	34.70972	35.05859	34.47949	0.072411	0.005243
110	34.12235	34.3584	33.71777	0.086161	0.007424
111	42.17258	42.5166	41.94727	0.065499	0.00429
112	41.41339	41.58887	41.21094	0.064194	0.004121
113	35.02194	35.21484	34.52344	0.083282	0.006936
114	32.00789	32.11719	31.9082	0.047771	0.002282
115 - Inlet Pipe	32.23669	32.44531	32.11914	0.060569	0.003669
116 - Zero Reference	0.039307	0.066406	0.003906	0.014403	0.000207
117 - Outlet Plenum	32.29709	32.34375	32.2373	0.021249	0.000452
118 - Inlet Plenum	18.50949	19.13281	17.56641	0.423555	0.179399
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
400	19.40492	19.47461	19.33984	0.02895	0.000838
401	32.74313	33.75684	32.61426	0.136168	0.018542
402	32.31334	32.35645	32.2168	0.025147	0.000632
403	34.27692	34.67773	34.12695	0.081514	0.006645
404	35.31786	35.50586	35.21582	0.048862	0.002387
405	36.13042	36.68262	35.89648	0.146397	0.021432
406	33.54317	33.82227	33.08887	0.193794	0.037556
407	35.15036	35.30762	34.92676	0.06748	0.004554
408	N/A	N/A	N/A	N/A	N/A
409	34.54453	34.75488	34.45605	0.050951	0.002596
410	N/A	N/A	N/A	N/A	N/A
411	32.51852	32.67871	32.38867	0.060007	0.003601
412	32.56595	32.64258	32.46289	0.047396	0.002246
413	32.61501	32.68164	32.52734	0.040324	0.001626
414 - Bath Temp	19.50726	20.26465	18.68262	0.371153	0.137755
415 - Replaced 410	36.68518	36.83203	36.29785	0.0734	0.005388
416 - Zero Reference	0.028015	0.201172	-0.21875	0.087199	0.007604

Figure 43. 250 Watts Heat Input at 15% Flow Rate

417 - Top of Plate	32.58939	32.99316	32.39648	0.081926	0.006712
418 - Ambient Air	17.02158	17.58301	16.71582	0.090212	0.008138
419 - bottom insulation	37.30475	37.46484	37.1582	0.056463	0.003188
420 Bottom Insulation	-76.6115	-52.1719	-103.742	14.22186	202.2613
421 -Side Insulation	19.24953	19.3125	19.16309	0.031165	0.000971
422 - Plate Top (over 27)	17.5573	17.80078	17.41992	0.068015	0.004626
423-Side of Plate	29.96733	30.1084	29.82031	0.060086	0.00361
v1 - Flowmeter	0.520382	0.536996	0.50902	0.005716	0.000033
v2 - Resistor	34.69889	34.6997	34.6981	0.000414	1.7E-07
v3 - Heater	74.17609	74.1766	74.1757	0.000187	3.5E-08
Bath Temp (C)	32.1				
Sampling Time	0.128182	0.144796	0.11682	0.005716	0.000033
Power	249.8862	249.8917	249.8812	0.002518	6.3E-06
Flowrate	21.29227	24.05206	19.40497		
Inlet Temperature	32.23669				
Centerline Mean Temp	35.36269				
Standard Deviation	3.009787		Delta Temp	3.26269	
Variance	9.058818				
Centerline Maximum Temp	42.17258				
Centerline Minimum Temp	32.00789				
Centerline Delta Temp	10.16469				

Figure 43. 250 Watts Heat Input at 15% Flow Rate

Pump Setting	20				
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
100	32.61304	32.77979	32.50928	0.041404	0.001958
101	33.80925	34.02637	33.6582	0.075495	0.005699
102	33.81379	34.15234	33.46973	0.092835	0.008618
103	39.15909	39.44238	38.98828	0.082204	0.006758
104	34.19204	34.33984	33.67285	0.090538	0.008197
105	34.07239	34.22656	33.66895	0.092302	0.00852
106	34.2809	34.42773	34.12305	0.064459	0.004155
107	33.84938	34.22949	33.6123	0.083615	0.006991
108	33.86002	34.36621	33.66797	0.103478	0.010708
109	34.72646	34.85547	34.62793	0.048254	0.002328
110	34.2216	34.44043	33.98633	0.085618	0.00733
111	42.18317	42.47266	41.98438	0.079564	0.00633
112	41.46361	42.09766	41.13672	0.106651	0.011375
113	35.03133	35.27051	34.80762	0.082958	0.006882
114	32.06202	33.19238	31.85938	0.158891	0.025246
115 - Inlet Pipe	32.2962	32.47852	32.11719	0.065611	0.004305
116 - Zero Reference	0.050376	0.080078	0.017578	0.013552	0.000184
117 - Outlet Plenum	32.27184	32.32617	32.22754	0.023933	0.000573
118 - Inlet Plenum	18.56295	19.13477	17.69824	0.316347	0.100075
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
400	19.55644	19.7666	19.48633	0.041646	0.001734
401	32.80778	33.04297	32.66895	0.057014	0.003251
402	32.4183	32.5166	32.34961	0.025794	0.000665
403	34.38673	34.73047	34.2041	0.091769	0.008421
404	35.40267	35.66211	35.20215	0.075781	0.005743
405	37.52045	37.83301	37.24902	0.082261	0.006767
406	33.72366	33.89844	33.3252	0.093921	0.008821
407	35.55658	36.29004	35.37891	0.120529	0.014527
408	N/A	N/A	N/A	N/A	N/A
409	34.55305	34.81445	34.27539	0.084794	0.00719
410	N/A	N/A	N/A	N/A	N/A
411	32.6901	32.95312	32.34961	0.095029	0.009031
412	32.71315	32.76367	32.68262	0.015455	0.000239
413	32.75856	32.83984	32.71875	0.015727	0.000247
414 - Bath Temp	19.50473	20.48926	18.70215	0.324519	0.105313
415 - Replaced 410	36.78075	37.28613	36.62109	0.089993	0.008099
416 - Zero Reference	0.107197	0.236328	-0.13574	0.072979	0.005326

Figure 44. 250 Watts Heat Input at 20% Flow Rate

417 - Top of Plate	32.59892	32.77344	32.24121	0.072904	0.005315
418 - Ambient Air	17.03645	17.34082	16.85742	0.089767	0.008058
419 - bottom insulation	37.04769	37.30762	36.77344	0.08455	0.007149
421 -Side Insulation	18.8012	19.00293	18.66309	0.079689	0.00635
422 - Plate Top (over 27)	17.51396	17.87207	17.07422	0.102023	0.010409
423-Side of Plate	29.53807	29.84668	29.27637	0.150423	0.022627
v1 - Flowmeter	0.528281	0.544564	0.520887	0.004189	0.000018
v2 - Resistor	34.6936	34.6946	34.6925	0.000608	3.7E-07
v3 - Heater	74.17682	74.1771	74.1766	0.00012	1.4E-08
Bath Temp (C)	32.2				
Sampling Time	0.136081	0.152364	0.128687	0.004189	0.000018
Power	249.8506	249.858	249.8433	0.004115	0.000017
Flowrate	22.60448	25.30918	21.3762		
Inlet Temperature	32.2962				
Centerline Mean Temp	35.48036				
Standard Deviation	2.978927		Delta Temp	3.280361	
Variance	8.874004				
Centerline Maximum Temp	42.18317				
Centerline Minimum Temp	32.06202				
Centerline Delta Temp	10.12115				
Centerline Delta Temp	6.2E+74	6.2E+74	6.2E+74		

Figure 44. 250 Watts Heat Input at 20% Flow Rate

Pump Setting	25				
T.C.	**Average**	**Maximum**	**Minimum**	**Std Dev.**	**Variance**
100	32.63862	33.07617	32.14258	0.002784	1.5E-07
101	33.7739	34.15137	33.54199	0.104591	0.010939
102	33.73885	34.16504	33.18652	0.124748	0.015562
103	39.19515	39.87402	38.28125	0.169993	0.028897
104	33.98239	34.375	33.58301	0.12471	0.015552
105	34.06672	34.44336	33.87793	0.092178	0.008497
106	34.29309	34.47363	34.13184	0.083382	0.006953
107	33.79872	34.49707	33.5918	0.143118	0.020483
108	33.74781	34.03125	33.39063	0.114848	0.01319
109	34.79072	35.48242	34.54004	0.140579	0.019762
110	34.18564	34.60547	33.8291	0.123711	0.015305
111	42.06941	42.61426	41.80664	0.1081	0.011686
112	41.34952	42.19824	40.49316	0.181945	0.033104
113	35.00116	35.36523	34.69531	0.110656	0.012245
114	31.88851	32.37305	31.58594	0.138152	0.019086
115 - Inlet Pipe	32.32906	33.24805	32.10742	0.140212	0.019659
116 - Zero Reference	0.209105	0.607422	0.039063	0.151747	0.023027
117 - Outlet Plenum	32.2442	32.29297	32.17871	0.028233	0.000797
118 - Inlet Plenum	18.1136	18.81543	17.47266	0.301478	0.090889
T.C.					
400	19.60066	19.70703	19.53516	0.036123	0.001305
401	32.91336	33.07617	32.70801	0.073464	0.005397
402	32.36388	32.4668	32.14258	0.067896	0.00461
403	34.36651	34.76855	33.76855	0.128846	0.016601
404	35.41882	35.82422	35.11133	0.107828	0.011627
405	37.46188	38.05273	37.16113	0.136465	0.018623
406	33.68078	33.9873	33.26855	0.126068	0.015893
407	35.56797	36.19238	35.23145	0.130296	0.016977
408	N/A	N/A	N/A	N/A	N/A
409	34.41952	34.80371	33.80371	0.155898	0.024304
410	N/A	N/A	N/A	N/A	N/A
411	32.54929	32.89063	32.12305	0.116311	0.013528
412	32.50666	32.63477	32.3291	0.081492	0.006641

Figure 45. 250 Watts Heat Input at 25% Flow Rate

413	32.58439	32.73535	32.4209	0.083469	0.006967
414 - Bath Temp	19.66188	20.29688	18.95801	0.339488	0.115252
415 - Replaced 410	36.57279	38.09082	36.125	0.24622	0.060625
416 - Zero Reference	0.035907	0.217773	-0.24023	0.10792	0.011647
417 - Top of Plate	32.4351	32.97559	32.20117	0.128136	0.016419
418 - Ambient Air	16.99988	17.37988	16.49316	0.100303	0.010061
419 - bottom insulation	37.26837	37.57715	36.43652	0.147756	0.021832
420 Bottom Insulation	221.4878	232.5732	204.8467	7.678248	58.9555
421 -Side Insulation	18.76865	19.16992	18.51855	0.141287	0.019962
422 - Plate Top (over 27)	17.44044	17.58496	17.27148	0.064396	0.004147
423-Side of Plate	28.06599	28.31738	27.80664	0.095857	0.009189
v1 - Flowmeter	0.535177	0.546487	0.52537	0.004135	0.000017
v2 - Resistor	34.68836	34.6898	34.6872	0.000748	5.6E-07
v3 - Heater	74.17698	74.1772	74.1767	0.000107	1.2E-08
Bath Temp (C)	32.1				
Sampling Time	0.142977	0.154287	0.13317	0.004135	0.000017
Power	249.8134	249.8235	249.8044	0.005317	0.000028
Flowrate	23.74989	25.62861	22.12087		
Inlet Temperature	32.32906				
Centerline Mean Temp	35.42011				
Standard Deviation	2.979942		Delta Temp	3.320113	
Variance	8.880057				
Centerline Maximum Temp	42.06941				
Centerline Minimum Temp	31.88851				
Centerline Delta Temp	10.1809				

Figure 45. 250 Watts Heat Input at 25% Flow Rate

Pump Setting	15		Run One		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	35.431	35.489	35.281	0.0427	0.0018
102	36.440	36.483	36.271	0.0385	0.0015
103	42.567	42.629	42.500	0.0293	0.0009
104	35.740	35.784	35.693	0.0196	0.0004
105	35.991	36.101	35.912	0.0327	0.0011
106	36.429	36.472	36.060	0.0678	0.0046
107	35.854	35.948	35.823	0.0374	0.0014
108	36.062	36.091	35.917	0.0313	0.0010
109	42.174	42.214	42.148	0.0134	0.0002
110	36.203	36.246	36.177	0.0143	0.0002
111	45.202	45.249	45.142	0.0277	0.0008
112	44.262	44.285	44.207	0.0210	0.0004
113	36.910	36.971	36.824	0.0288	0.0008
114	35.715	35.903	35.661	0.0604	0.0037
115-Inlet Pipe	34.261	34.338	34.227	0.0303	0.0009
116 - Zero Reference	0.120	0.144	0.075	0.0125	0.0002
117 - Outlet Plenum	34.423	34.445	34.386	0.0163	0.0003
118 - Inlet Plenum	19.752	20.281	18.370	0.4852	0.2354
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.374	20.067	19.220	0.1703	0.0290
401	34.745	34.852	34.711	0.0409	0.0017
402	34.604	34.654	34.556	0.0262	0.0007
403	37.221	37.246	37.169	0.0200	0.0004
404	38.009	38.024	37.991	0.0078	0.0001
405	39.555	39.616	39.453	0.0516	0.0027
406	35.785	35.811	35.626	0.0293	0.0009
407	38.250	38.280	38.188	0.0164	0.0003
408	N/A	N/A	N/A	N/A	N/A
409	37.104	37.156	37.020	0.0376	0.0014
410	N/A	N/A	N/A	N/A	N/A
411	34.966	34.990	34.906	0.0183	0.0003
412	34.824	34.854	34.770	0.0156	0.0002

Figure 46. 275 Watts Heat Input at 15% Flow Rate

413	34.883	34.916	34.849	0.0117	0.0001
414 - Bath Temp	19.997	20.556	19.279	0.3678	0.1353
415 - Replaced 410	24.542	39.668	23.952	7.6520	58.5535
416 - Zero Reference	0.262	0.540	-0.243	0.2026	0.0410
417 - Top of Plate	34.919	34.964	34.753	0.0382	0.0015
418 - Ambient Air	17.872	17.979	17.789	0.0444	0.0020
419 - Bottom Insulation	41.433	41.482	41.318	0.0445	0.0020
421 - Side Insulation	20.397	20.661	19.915	0.2559	0.0655
422 - Plate Top (over 417)	21.110	21.300	20.952	0.0749	0.0056
423 - Side of Plate	32.031	32.159	31.811	0.0696	0.0048
V1 - Flow Meter Vdc	0.528	0.544	0.520	0.0060	0.0000
V2 - Precision Resistor Vdc	36.251	36.254	36.245	0.0036	0.0000
V3 - Heater Terminals Vdc	77.590	77.590	77.590	0.0002	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.136	0.152	0.128	0.0060	0.0000
Power (watts)	273.077	273.103	273.031	0.0278	0.0008
Flow Rate (mL/sec)	22.635	25.242	21.192		
	Plate Mean	Temperature			
Centerline Mean Temp	38.213				
Standard Deviation	3.458		Delta Temp	3.2128	
Variance	11.955				
Centerline Maximum Temp	45.202	45.249	45.142	0.0678	0.0046
Centerline Minimum Temp	35.431	35.489	35.281	0.0134	0.0002
Centerline Delta Temp	9.771	9.760	9.860	0.0544	0.0044

Figure 46. 275 Watts Heat Input at 15% Flow Rate

Pump Setting	15		Run Two		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	32.882	34.785	32.845	0.520	0.2707
101	35.329	35.366	35.234	0.041	0.0017
102	36.431	36.466	36.370	0.025	0.0006
103	42.437	42.496	42.390	0.024	0.0006
104	35.806	35.829	35.778	0.013	0.0002
105	35.987	36.024	35.862	0.054	0.0029
106	36.459	36.484	36.433	0.011	0.0001
107	35.922	35.948	35.896	0.014	0.0002
108	35.974	35.997	35.950	0.011	0.0001
109	42.223	42.243	42.180	0.014	0.0002
110	36.155	36.171	36.131	0.008	0.0001
111	45.160	45.181	45.130	0.012	0.0001
112	44.236	44.260	44.209	0.013	0.0002
113	36.913	36.939	36.885	0.014	0.0002
114	35.859	35.874	35.835	0.009	0.0001
115-Inlet Pipe	34.339	34.361	34.309	0.011	0.0001
116 - Zero Reference	0.119	0.168	0.063	0.023	0.0005
117 - Outlet Plenum	34.423	34.459	34.384	0.018	0.0003
118 - Inlet Plenum	19.737	20.417	18.607	0.534	0.2851
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.192	19.808	19.090	0.173	0.0299
401	34.816	35.178	34.689	0.077	0.0060
402	34.617	34.650	34.556	0.022	0.0005
403	37.126	37.145	37.082	0.015	0.0002
404	38.002	38.047	37.979	0.014	0.0002
405	39.575	39.610	39.550	0.016	0.0003
406	35.770	35.787	35.724	0.013	0.0002
407	38.184	38.215	38.158	0.015	0.0002
408	N/A	N/A	N/A	N/A	N/A
409	37.079	37.109	37.056	0.013	0.0002
410	N/A	N/A	N/A	N/A	N/A
411	34.955	34.985	34.929	0.013	0.0002
412	34.827	34.847	34.771	0.014	0.0002

Figure 47. 275 Watts Heat Input at 15% Flow Rate

413	34.870	34.896	34.845	0.012	0.0002
414 - Bath Temp	20.020	20.646	19.156	0.374	0.1402
415 - Replaced 410	39.652	40.229	39.286	0.225	0.0507
416 - Zero Reference	0.181	0.489	-0.511	0.209	0.0435
417 - Top of Plate	34.880	34.912	34.818	0.024	0.0006
418 - Ambient Air	17.760	17.802	17.732	0.015	0.0002
419 - Bottom Insulation	41.202	41.248	41.150	0.025	0.0006
421 - Side Insulation	21.516	22.131	20.380	0.624	0.3898
422 - Plate Top (over 417)	21.247	21.369	21.061	0.060	0.0036
423 - Side of Plate	30.974	31.271	30.776	0.131	0.0171
V1 - Flow Meter Vdc	0.524	0.538	0.511	0.005	0.0000
V2 - Precision Resistor Vdc	36.241	36.246	36.237	0.001	0.0000
V3 - Heater Terminals Vdc	77.589	77.590	77.589	0.000	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.132	0.146	0.119	0.005	0.0000
Power (watts)	273.003	273.036	272.973	0.011	0.0001
Flow Rate (mL/sec)	21.944	24.282	19.758	-90.887	-91.9051
	Plate Mean	Temperature			
Centerline Mean Temp	38.207				
Standard Deviation	3.438		Delta Temp	3.207	
Variance	11.821				
Centerline Maximum Temp	45.160	45.181	45.130	0.054	0.0029
Centerline Minimum Temp	35.329	35.366	35.234	0.008	0.0001
Centerline Delta Temp	9.831	9.814	9.895	0.045	0.0028

Figure 47. 275 Watts Heat Input at 15% Flow Rate

Pump Setting	15		Run Three		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	33.682	33.912	33.497	0.0626	0.0039
102	33.669	33.858	33.527	0.0574	0.0033
103	39.012	39.146	38.753	0.0549	0.0030
104	33.881	34.138	33.696	0.0558	0.0031
105	33.760	34.202	33.587	0.0829	0.0069
106	34.135	34.370	33.921	0.0657	0.0043
107	33.725	33.832	33.542	0.0483	0.0023
108	33.744	33.979	33.563	0.0685	0.0047
109	34.701	35.059	34.479	0.0724	0.0052
110	34.125	34.358	33.718	0.0862	0.0074
111	42.172	42.517	41.947	0.0655	0.0043
112	41.422	41.589	41.211	0.0642	0.0041
113	35.027	35.215	34.523	0.0833	0.0069
114	32.009	32.117	31.908	0.0478	0.0023
115-Inlet Pipe	32.224	32.445	32.119	0.0606	0.0037
116 - Zero Reference	0.041	0.066	0.004	0.0144	0.0002
117 - Outlet Plenum	32.297	32.344	32.237	0.0212	0.0005
118 - Inlet Plenum	18.586	19.133	17.566	0.4236	0.1794
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.408	19.475	19.340	0.0289	0.0008
401	32.729	33.757	32.614	0.1362	0.0185
402	32.315	32.356	32.217	0.0251	0.0006
403	34.267	34.678	34.127	0.0815	0.0066
404	35.313	35.506	35.216	0.0489	0.0024
405	36.073	36.683	35.896	0.1464	0.0214
406	33.634	33.822	33.089	0.1938	0.0376
407	35.138	35.308	34.927	0.0675	0.0046
408	N/A	N/A	N/A	N/A	N/A
409	34.538	34.755	34.456	0.0510	0.0026
410	N/A	N/A	N/A	N/A	N/A
411	32.519	32.679	32.389	0.0600	0.0036
412	32.573	32.643	32.463	0.0474	0.0022

Figure 48. 275 Watts Heat Input at 15% Flow Rate

413	32.625	32.682	32.527	0.0403	0.0016
414 - Bath Temp	19.488	20.265	18.683	0.3712	0.1378
415 - Replaced 410	36.686	36.832	36.298	0.0734	0.0054
416 - Zero Reference	0.050	0.201	-0.219	0.0872	0.0076
417 - Top of Plate	32.582	32.993	32.396	0.0819	0.0067
418 - Ambient Air	17.009	17.583	16.716	0.0902	0.0081
419 - Bottom Insulation	37.304	37.465	37.158	0.0565	0.0032
421 - Side Insulation	19.249	19.313	19.163	0.0312	0.0010
422 - Plate Top (over 417)	17.544	17.801	17.420	0.0680	0.0046
423 - Side of Plate	29.968	30.108	29.820	0.0601	0.0036
V1 - Flow Meter Vdc	0.519	0.537	0.509	0.0057	0.0000
V2 - Precision Resistor Vdc	34.699	34.700	34.698	0.0004	0.0000
V3 - Heater Terminals Vdc	74.176	74.177	74.176	0.0002	0.0000
Bath Temp (C)	32.2				
Sampling Time	0.127	0.145	0.117	0.0057	0.0000
Power (watts)	249.886	249.892	249.881	0.0025	0.0000
Flow Rate (mL/sec)	21.091	24.052	19.405		
	Plate Mean	Temperature			
Centerline Mean Temp	35.362				
Standard Deviation	3.012		Delta Temp	3.1619	
Variance	9.071				
Centerline Maximum Temp	42.172	42.517	41.947	0.0862	0.0074
Centerline Minimum Temp	32.009	32.117	31.908	0.0478	0.0023
Centerline Delta Temp	10.163	10.399	10.039	0.0384	0.0051

Figure 48. 275 Watts Heat Input at 15% Flow Rate

Pump Setting	20		Run One		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	35.229	35.306	35.167	0.0439	0.0019
102	36.299	36.348	36.259	0.0270	0.0007
103	41.103	41.124	41.072	0.0129	0.0002
104	36.083	36.117	36.064	0.0130	0.0002
105	35.839	35.859	35.805	0.0142	0.0002
106	36.063	36.110	35.960	0.0398	0.0016
107	35.925	35.949	35.896	0.0127	0.0002
108	35.886	36.011	35.846	0.0299	0.0009
109	42.230	42.266	42.209	0.0172	0.0003
110	36.115	36.153	36.091	0.0118	0.0001
111	45.018	45.063	44.982	0.0240	0.0006
112	44.068	44.087	44.039	0.0128	0.0002
113	36.866	36.888	36.850	0.0101	0.0001
114	35.706	35.721	35.687	0.0088	0.0001
115-Inlet Pipe	34.240	34.262	34.181	0.0149	0.0002
116 - Zero Reference	0.088	0.117	0.049	0.0155	0.0002
117 - Outlet Plenum	34.368	34.430	34.328	0.0254	0.0006
118 - Inlet Plenum	19.924	20.542	18.557	0.4040	0.1632
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.132	19.327	19.015	0.0663	0.0044
401	34.770	34.853	34.699	0.0381	0.0015
402	34.579	34.612	34.541	0.0182	0.0003
403	36.663	36.711	36.641	0.0177	0.0003
404	37.500	37.519	37.471	0.0134	0.0002
405	38.989	39.331	38.959	0.1396	0.0195
406	35.745	35.774	35.723	0.0122	0.0001
407	38.034	38.063	38.013	0.0106	0.0001
408	N/A	N/A	N/A	N/A	N/A
409	36.931	36.974	36.907	0.0150	0.0002
410	N/A	N/A	N/A	N/A	N/A
411	34.905	34.932	34.876	0.0148	0.0002
412	34.781	34.799	34.753	0.0116	0.0001

Figure 49. 275 Watts Heat Input at 20% Flow Rate

413	34.834	34.858	34.812	0.0128	0.0002
414 - Bath Temp	20.440	21.203	19.834	0.3018	0.0911
415 - Replaced 410	39.504	39.806	39.269	0.1269	0.0161
416 - Zero Reference	0.282	0.625	-0.229	0.2133	0.0455
417 - Top of Plate	34.761	34.824	34.723	0.0213	0.0005
418 - Ambient Air	17.824	17.871	17.785	0.0219	0.0005
419 - Bottom Insulation	39.357	39.431	38.711	0.2048	0.0419
	*************	*************	-39.378	*************	*************
421 - Side Insulation	21.289	21.508	20.742	0.2492	0.0621
422 - Plate Top (over 417)	21.694	21.752	21.507	0.0454	0.0021
423 - Side of Plate	31.521	31.633	31.429	0.0467	0.0022
V1 - Flow Meter Vdc	0.523	0.533	0.507	0.0047	0.0000
V2 - Precision Resistor Vdc	36.219	36.220	36.219	0.0003	0.0000
V3 - Heater Terminals Vdc	77.588	77.588	77.588	0.0001	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.131	0.141	0.115	0.0047	0.0000
Power (watts)	272.833	272.840	272.827	0.0029	0.0000
Flow Rate (mL/sec)	21.710	23.356	19.050		
	Plate Mean	Temperature			
Centerline Mean Temp	38.031				
Standard Deviation	3.329		Delta Temp	3.0308	
Variance	11.081				
Centerline Maximum Temp	45.018	45.063	44.982	0.0439	0.0019
Centerline Minimum Temp	35.229	35.306	35.167	0.0088	0.0001
Centerline Delta Temp	9.789	9.758	9.815	0.0351	0.0018

Figure 49. 275 Watts Heat Input at 20% Flow Rate

Pump Setting	20		Run Two		
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	35.227	35.323	35.201	0.0312	0.0010
102	36.335	36.369	36.284	0.0155	0.0002
103	41.127	41.154	41.095	0.0133	0.0002
104	36.122	36.176	36.095	0.0179	0.0003
105	35.848	35.876	35.777	0.0195	0.0004
106	36.041	36.073	35.980	0.0202	0.0004
107	35.949	35.971	35.914	0.0128	0.0002
108	35.901	36.013	35.856	0.0333	0.0011
109	42.222	42.269	42.155	0.0225	0.0005
110	36.119	36.146	36.080	0.0138	0.0002
111	45.087	45.108	45.046	0.0159	0.0003
112	44.066	44.112	43.914	0.0315	0.0010
113	36.859	36.918	36.817	0.0217	0.0005
114	35.714	35.742	35.680	0.0119	0.0001
115-Inlet Pipe	34.274	34.305	34.249	0.0128	0.0002
116 - Zero Reference	0.098	0.156	-0.003	0.0280	0.0008
117 - Outlet Plenum	34.409	34.449	34.345	0.0249	0.0006
118 - Inlet Plenum	19.939	20.416	18.688	0.4787	0.2292
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.082	19.321	18.997	0.0832	0.0069
401	34.813	35.088	34.722	0.0856	0.0073
402	34.619	34.646	34.572	0.0188	0.0004
403	36.675	36.709	36.654	0.0115	0.0001
404	37.537	37.570	37.521	0.0111	0.0001
405	39.031	39.061	38.955	0.0326	0.0011
406	35.760	35.782	35.740	0.0114	0.0001
407	38.056	38.070	38.030	0.0102	0.0001
408	N./A	N./A	N./A	N./A	N./A
409	36.949	36.994	36.917	0.0150	0.0002
410	N./A	N./A	N./A	N./A	N./A
411	34.851	34.881	34.791	0.0235	0.0006
412	34.725	34.765	34.641	0.0305	0.0009

Figure 50. 275 Watts Heat Input at 20% Flow Rate

413	34.784	34.885	34.739	0.0312	0.0010
414 - Bath Temp	20.520	21.064	19.839	0.3066	0.0940
415 - Replaced 410	39.477	40.123	39.136	0.1591	0.0253
416 - Zero Reference	0.144	0.544	-0.527	0.2635	0.0695
417 - Top of Plate	34.748	34.830	34.688	0.0318	0.0010
418 - Ambient Air	17.828	20.684	17.750	0.6506	0.4232
419 - Bottom Insulation	39.353	39.372	39.331	0.0108	0.0001
421 - Side Insulation	20.513	20.645	20.417	0.0527	0.0028
422 - Plate Top (over 417)	21.595	21.728	21.464	0.0636	0.0040
423 - Side of Plate	31.317	31.522	31.087	0.1005	0.0101
V1 - Flow Meter Vdc	0.523	0.536	0.517	0.0038	0.0000
V2 - Precision Resistor Vdc	36.221	36.224	36.220	0.0014	0.0000
V3 - Heater Terminals Vdc	77.588	77.588	77.588	0.0001	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.131	0.144	0.124	0.0038	0.0000
Power (watts)	272.847	272.868	272.838	0.0104	0.0001
Flow Rate (mL/sec)	21.759	23.894	20.653		
	Plate Mean	Temperature			
Centerline Mean Temp	38.044				
Standard Deviation	3.335		Delta Temp	3.0441	
Variance	11.124				
Centerline Maximum Temp	45.087	45.108	45.046	0.0333	0.0011
Centerline Minimum Temp	35.227	35.323	35.201	0.0119	0.0001
Centerline Delta Temp	9.860	9.785	9.845	0.0214	0.0010

Figure 50. 275 Watts Heat Input at 20% Flow Rate

Pump Setting	25				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	35.928	35.954	35.898	0.0147	0.0002
102	36.265	36.295	36.242	0.0123	0.0002
103	41.097	41.141	41.066	0.0186	0.0003
104	36.198	36.221	36.153	0.0153	0.0002
105	36.032	36.076	35.960	0.0311	0.0010
106	36.211	36.276	36.069	0.0603	0.0036
107	35.852	35.882	35.813	0.0176	0.0003
108	36.035	36.063	36.001	0.0149	0.0002
109	41.768	41.822	41.642	0.0503	0.0025
110	36.156	36.245	36.102	0.0429	0.0018
111	44.926	44.955	44.897	0.0170	0.0003
112	44.047	44.064	44.010	0.0146	0.0002
113	37.021	37.065	36.974	0.0233	0.0005
114	35.986	36.053	35.661	0.0782	0.0061
115-Inlet Pipe	34.387	34.411	34.344	0.0144	0.0002
116 - Zero Reference	0.069	0.152	0.033	0.0273	0.0007
117 - Outlet Plenum	34.395	34.427	34.355	0.0163	0.0003
118 - Inlet Plenum	20.462	20.819	18.866	0.5512	0.3038
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	19.987	20.086	19.903	0.0420	0.0018
401	34.788	34.842	34.747	0.0256	0.0007
402	34.607	34.636	34.568	0.0188	0.0004
403	36.624	36.685	36.594	0.0230	0.0005
404	37.436	37.467	37.419	0.0106	0.0001
405	40.259	40.313	40.167	0.0492	0.0024
406	35.776	35.803	35.749	0.0128	0.0002
407	38.127	38.196	38.012	0.0607	0.0037
408	N/A	N/A	N/A	N/A	N/A
409	36.836	36.872	36.790	0.0251	0.0006
410	N/A	N/A	N/A	N/A	N/A
411	34.915	34.952	34.893	0.0126	0.0002
412	34.810	34.836	34.782	0.0111	0.0001

Figure 51. 275 Watts Heat Input at 25% Flow Rate

413	34.855	34.877	34.824	0.0121	0.0001
414 - Bath Temp	20.577	21.169	19.917	0.3285	0.1079
415 - Replaced 410	39.682	39.960	39.484	0.1326	0.0176
416 - Zero Reference	0.389	0.650	-0.373	0.2165	0.0469
417 - Top of Plate	34.696	34.735	34.636	0.0232	0.0005
418 - Ambient Air	18.086	18.149	18.005	0.0440	0.0019
419 - Bottom Insulation	38.837	38.961	38.793	0.0560	0.0031
421 - Side Insulation	21.026	21.644	20.297	0.4416	0.1950
422 - Plate Top (over 417)	22.386	22.431	22.317	0.0329	0.0011
423 - Side of Plate	32.829	33.107	32.712	0.1068	0.0114
V1 - Flow Meter Vdc	0.536	0.548	0.527	0.0044	0.0000
V2 - Precision Resistor Vdc	36.201	36.202	36.200	0.0006	0.0000
V3 - Heater Terminals Vdc	77.585	77.585	77.584	0.0002	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.144	0.156	0.135	0.0044	0.0000
Power (watts)	272.682	272.693	272.674	0.0051	0.0000
Flow Rate (mL/sec)	23.842	25.884	22.372		
	Plate Mean	Temperature			
Centerline Mean Temp	38.109				
Standard Deviation	3.192		Delta Temp	3.1086	
Variance	10.191				
Centerline Maximum Temp	44.926	44.955	44.897	0.0782	0.0061
Centerline Minimum Temp	35.852	35.882	35.661	0.0123	0.0002
Centerline Delta Temp	9.074	9.073	9.236	0.0659	0.0060

Figure 51. 275 Watts Heat Input at 25% Flow Rate

Pump Setting	30				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	24.137	24.173	23.956	0.0332	0.0011
102	24.336	24.390	24.259	0.0230	0.0005
103	30.294	30.334	30.243	0.0195	0.0004
104	24.518	24.640	24.450	0.0323	0.0010
105	24.377	24.645	24.291	0.0894	0.0080
106	24.880	24.916	24.799	0.0237	0.0006
107	23.802	24.390	23.690	0.1804	0.0326
108	24.298	24.330	24.244	0.0216	0.0005
109	25.459	25.506	25.408	0.0184	0.0003
110	24.638	24.675	24.417	0.0671	0.0045
111	28.178	28.220	28.113	0.0248	0.0006
112	30.856	30.905	30.787	0.0232	0.0005
113	24.963	25.014	24.910	0.0194	0.0004
114	24.053	24.325	24.014	0.0509	0.0026
115-Inlet Pipe	22.629	22.668	22.491	0.0393	0.0015
116 - Zero Reference	0.005	0.102	-0.096	0.0370	0.0014
117 - Outlet Plenum	22.304	22.389	22.212	0.0382	0.0015
118 - Inlet Plenum	18.257	18.765	17.141	0.3830	0.1467
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	18.092	18.483	17.959	0.1234	0.0152
401	23.215	23.252	23.154	0.0231	0.0005
402	22.951	22.985	22.898	0.0176	0.0003
403	25.670	25.700	25.616	0.0160	0.0003
404	26.700	26.738	26.651	0.0181	0.0003
405	28.935	28.961	28.893	0.0143	0.0002
406	24.927	24.959	24.865	0.0197	0.0004
407	26.285	26.332	26.240	0.0195	0.0004
408	N./A	N./A	N./A	N./A	N./A
409	27.186	27.233	27.115	0.0244	0.0006
410	N./A	N./A	N./A	N./A	N./A
411	23.296	23.468	23.256	0.0603	0.0036
412	23.398	23.445	23.360	0.0232	0.0005

Figure 52. 275 Watts Heat Input at 30% Flow Rate

413	23.346	23.383	23.294	0.0219	0.0005
414 - Bath Temp	17.757	18.958	17.000	0.3720	0.1384
415 - Replaced 410	25.912	25.982	25.851	0.0282	0.0008
416 - Zero Reference	-0.050	0.086	-0.228	0.0591	0.0035
417 - Top of Plate	22.771	22.928	22.696	0.0446	0.0020
418 - Ambient Air	16.477	16.571	16.357	0.0618	0.0038
419 - Bottom Insulation	29.477	29.514	29.433	0.0214	0.0005
421 - Side Insulation	18.199	18.612	17.957	0.1710	0.0293
422 - Plate Top (over 417)	16.519	16.562	16.487	0.0142	0.0002
423 - Side of Plate	21.639	21.973	21.367	0.1447	0.0209
V1 - Flow Meter Vdc	0.592	0.656	0.528	0.0396	0.0016
V2 - Precision Resistor Vdc	0.366	0.368	0.366	0.0007	0.0000
V3 - Heater Terminals Vdc	40.653	40.653	40.652	0.0002	0.0000
Bath Temp (C)	22.2				
Sampling Time	0.199	0.264	0.136	0.0396	0.0016
Power (watts)	147.404	148.152	147.176	0.2737	0.0749
Flow Rate (mL/sec)	33.130	43.829	22.549		
	Plate Mean	Temperature			
Centerline Mean Temp	25.628				
Standard Deviation	2.266		Delta Temp	3.4277	
Variance	5.136				
Centerline Maximum Temp	30.856	30.905	30.787	0.1804	0.0326
Centerline Minimum Temp	23.802	24.173	23.690	0.0184	0.0003
Centerline Delta Temp	7.055	6.732	7.097	0.1621	0.0322

Figure 52. 275 Watts Heat Input at 30% Flow Rate

Pump Setting	40				
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
100	N/A	N/A	N/A	N/A	N/A
101	35.462	35.982	31.809	1.4785	2.1859
102	35.964	36.413	32.344	1.4382	2.0685
103	40.989	41.150	37.863	1.0841	1.1753
104	35.932	36.199	32.396	1.3132	1.7246
105	35.818	36.018	32.440	1.2162	1.4791
106	36.276	36.476	32.472	1.3289	1.7659
107	35.747	35.879	32.431	1.1449	1.3107
108	35.748	35.844	32.186	1.2350	1.5251
109	41.657	41.731	38.641	1.0167	1.0337
110	36.082	36.222	32.913	1.1132	1.2391
111	43.315	44.030	40.569	1.0195	1.0394
112	39.536	40.826	36.443	1.2520	1.5674
113	36.645	36.724	33.783	0.9510	0.9044
114	35.813	35.886	32.959	0.9516	0.9055
115-Inlet Pipe	31.191	34.512	28.579	2.2733	5.1679
116 - Zero Reference	0.060	0.336	-0.141	0.0604	0.0036
117 - Outlet Plenum	31.570	34.363	27.603	2.5782	6.6470
118 - Inlet Plenum	20.295	20.736	18.542	0.4610	0.2125
T.C.	Average	Maximum	Minimum	Std Dev.	Variance
400	20.982	21.301	20.813	0.1261	0.0159
401	34.477	34.971	31.184	1.2896	1.6631
402	34.250	34.470	31.095	1.1633	1.3533
403	36.429	36.838	33.054	1.2824	1.6445
404	37.189	37.393	33.866	1.2489	1.5597
405	39.737	39.813	37.302	0.8115	0.6585
406	35.698	35.758	32.411	1.1550	1.3341
407	37.954	38.067	35.236	0.9143	0.8359
408	N/A	N/A	N/A	N/A	N/A
409	36.340	36.448	33.618	0.9122	0.8321
410	N/A	N/A	N/A	N/A	N/A
411	34.693	34.799	33.716	0.2894	0.0838
412	34.567	34.659	33.614	0.2799	0.0783

Figure 53. 275 Watts Heat Input at 40% Flow Rate

413	34.641	34.730	33.376	0.3912	0.1531
414 - Bath Temp	20.513	20.996	19.678	0.2867	0.0822
415 - Replaced 410	39.426	39.738	36.441	1.0065	1.0131
416 - Zero Reference	0.158	0.416	-0.590	0.2262	0.0511
417 - Top of Plate	34.434	34.594	31.991	0.7842	0.6150
418 - Ambient Air	18.455	18.515	18.403	0.0243	0.0006
419 - Bottom Insulation	37.657	37.817	34.997	0.8891	0.7906
421 - Side Insulation	21.067	21.313	20.593	0.2037	0.0415
422 - Plate Top (over 417)	22.698	22.883	22.587	0.0603	0.0036
423 - Side of Plate	33.041	33.497	30.029	1.0902	1.1885
V1 - Flow Meter Vdc	0.624	0.664	0.613	0.0105	0.0001
V2 - Precision Resistor Vdc	36.201	36.207	36.199	0.0022	0.0000
V3 - Heater Terminals Vdc	77.584	77.584	77.584	0.0002	0.0000
Bath Temp (C)	35.0				
Sampling Time	0.232	0.272	0.220	0.0105	0.0001
Power (watts)	272.677	272.726	272.665	0.0172	0.0003
Flow Rate (mL/sec)	38.520	45.217	36.616		
	Plate Mean	Temperature			
Centerline Mean Temp	37.499				
Standard Deviation	2.570		Delta Temp	2.4989	
Variance	6.604				
Centerline Maximum Temp	43.315	44.030	40.569	1.4785	2.1859
Centerline Minimum Temp	35.462	35.844	31.809	0.9510	0.9044
Centerline Delta Temp	7.854	8.187	8.761	0.5275	1.2815

Figure 53. 275 Watts Heat Input at 40% Flow Rate

Colburn j Factor Spreadsheet

Dh (m)	Q (ml/sec)	v (m/s)	Tavg	Tin	T prop	density	viscosity	sp heat	power	flux	thermal cond
0.0164	154.08	0.0441	37.5	31.2	34.3	993.9	0.00076	0.00015	273	3522	0.622
0.0164	110.416	0.0316	38.1	34.4	36.2	993.7	0.00074	0.00015	273	3522	0.62496
0.0164	107.716	0.0308	34.6	31.8	33.2	994.3	0.00076	0.00015	211	2719	0.6208
0.0164	98.636	0.0282	35.5	32.3	33.9	994.1	0.00075	0.00015	250	3227	0.623
0.0164	97.692	0.028	35.4	32.2	33.8	994.2	0.00076	0.00015	250	3228	0.6228
0.0164	98.636	0.0282	34.8	32.3	33.6	994.3	0.00077	0.00015	211	2720	0.6204
0.0164	95.368	0.0273	34.1	32.2	33.2	994.3	0.00076	0.00015	215	2773	0.6208
0.0164	90.276	0.0258	38.2	34.3	36.2	993.7	0.00073	0.00015	273	3527	0.62496
0.0164	110.416	0.0316	26	22.7	24.4	997.4	0.0009	0.00015	146	1888	0.609905
0.0164	89.388	0.0256	38.2	34.3	36.3	993.7	0.00073	0.00015	273	3526	0.62496
0.0164	90.54	0.0259	35.4	32.3	33.8	994.2	0.00076	0.00015	250	3228	0.6228
0.0164	90.54	0.0259	34.9	32.3	33.6	994.3	0.00077	0.00015	211	2720	0.6204
0.0164	85.16908	0.0244	34.2	32.3	33.3	994.3	0.00076	0.00015	211	2720	0.6208
0.0164	85.224	0.0244	35.4	32.2	33.8	994.2	0.00076	0.00015	211	2720	0.6228
0.0164	87.776	0.0251	26	22.8	24.4	997.4	0.0009	0.00015	146	1890	0.609905
0.0164	86.84	0.0249	26	22.7	24.4	997.4	0.0009	0.00015	146	1888	0.609905
0.0164	84.364	0.0242	25.2	20.7	23	997.8	0.00091	0.00015	99.1	1281	0.608769
0.0164	7.2	0.0021	38	34.2	36.1	993.7	0.00074	0.00015	273	3524	0.62496
Dh (m)	**Q (ml/sec)**	**v (m/s)**	**Tavg**	**Tin**	**T prop**	**density**	**viscosity**	**sp heat**	**power**	**flux**	**thermal cond**

Delta T	Nu_avg	Pr	Reynolds	j	j_weiting	j_M&B	j_J&W		Nu	j_low	j_high
2.5	26.79	5.02	942.5	0.0166	0.0121	0.0122	0.0154	1	10.5059	0.0153	0.018
3.11	22.07	4.88	693.77	0.0188	0.0142	0.0144	0.018	2	8.12954	0.0173	0.0203
2.44	21.37	5.24	663.18	0.0185	0.0146	0.0148	0.0184	3	8.06801	0.0171	0.0201
3.32	18.54	5.03	616.62	0.0175	0.0151	0.0154	0.0191	4	7.48808	0.0161	0.019
3.28	18.77	5.05	600.89	0.0182	0.0154	0.0156	0.0193	5	7.34648	0.0168	0.0198
2.05	25.43	5.08	597.16	0.0248	0.0154	0.0156	0.0194	6	7.3273	0.0228	0.0269
1.91	27.85	5.24	587.16	0.0273	0.0155	0.0158	0.0196	7	7.31921	0.0251	0.0296
3.21	20.87	4.88	579.43	0.0212	0.0157	0.0159	0.0197	8	7.03881	0.0195	0.023
3.89	9.451	5.12	574.54	0.0095	0.0157	0.016	0.0198	9	7.12675	0.0088	0.0104
3.21	20.9	4.88	573.73	0.0215	0.0157	0.016	0.0198	10	6.98337	0.0198	0.0233
3.16	19.55	5.05	556.9	0.0205	0.016	0.0162	0.0201	11	6.91296	0.0188	0.0222
12.8	4.08	5.08	548.14	0.0043	0.0161	0.0164	0.0203	12	6.84208	0.004	0.0047
1.41	36.95	5.24	524.37	0.0406	0.0165	0.0168	0.0207	13	6.68602	0.0373	0.044
3.26	15.9	5.05	524.2	0.0177	0.0165	0.0168	0.0207	14	6.5863	0.0163	0.0192
3.88	9.492	5.12	456.73	0.0121	0.0178	0.0181	0.0222	15	5.93153	0.0111	0.0131
3.79	9.7	5.12	451.86	0.0125	0.0179	0.0182	0.0223	16	5.88088	0.0115	0.0135
3.22	7.761	6.29	432.09	0.0097	0.0183	0.0186	0.0228	17	6.16098	0.009	0.0106
3.03	22.18	4.88	45.239	0.2891	0.0614	0.063	0.0705	18	0.91518	0.2659	0.3136
Delta T	**Nu_avg**	**Pr**	**Reynolds**	**j**	**j_weiting**	**j_M&B**	**j_J&W**		**Nu**	**j_low**	**j_high**

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